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Heat Transfer in the LCCM Thermal Reserve Battery

by Frank C. Krieger and Michael Ding

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14. ABSTRACT Volumetric energy densities of the LCCM (Low Cost Competent Munition) thermal battery were increased by ~25% over those of a previously miniaturized benchmark LCCM battery primarily by using improved battery construction and thermal management techniques (*1*,*2*). Experimental results and calculations indicate that the LCCM benchmark battery thermal lifetimes can be increased by ~200% over the original benchmark value of 90 s, and that the volumetric energy density can be increased to ~60 Wh/l by reducing the external package size and by using improved gas control methods with thermal cell heat generation in the near future. Thermal battery heat loss rates can be reduced by altering materials selection, chemical processing, battery construction, and gas control methods. Thermal cell heat generation rates and amounts can be increased by altering chemical processing and thermal cell construction methods. Increased axial forces and higher operating temperatures resulted in increased heat generation rates for normally operating thermal cells. Recently developed inertial igniters functioned properly in flight and air gun tests.						
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1. Introduction

The previously miniaturized (*2*) Low Cost Competent Munition (LCCM) thermal battery was chosen as a benchmark for a U.S. Army Research Laboratory (ARL) Army Technical Objective (ATO) to investigate thermal management optimization methods for thermal batteries. The external flight case of the benchmark LCCM thermal battery, excluding the inertial starter mechanism, was 33.32 mm (1.312 in.) in diameter by 35.79 mm (1.409 in.) tall, and those dimensions were held constant for this miniaturization study. The LCCM benchmark thermal battery volumetric energy density was low (~16.5 Wh/l) in this LCCM configuration because of heat transfer considerations (*2*). During operation the LCCM thermal battery is required to spin at a rate as high as 300 revolutions per second (RPS) and survive setback forces as high as 16,000 g. The LCCM thermal battery, therefore, requires a mechanically strong, high density thermal insulation, which means that the thermal insulation package will ordinarily have a relatively high global thermal conductivity value. The benchmark battery for the present ATO was built using construction methods similar to those used for a previously developed high spin LCCM thermal battery design that had a 159 A–s electrochemical capacity (*3*). The benchmark batteries for the present study used a 194 A–s electrochemical capacity thermal cell stack and delivered ~90 s to 11 V at 1.5 A in a heavy metal reusable test fixture (RTF) at –40 ºC ambient temperature. A 307 A–s thermal cell stack and insulation package which should deliver ~205 s of useful electrochemical lifetime at a current of 1.5 A was then developed for the flight test batteries used in the present study (table 1).

Table 1. LCCM thermal battery characteristics (enhanced 307 A–s capacity thermal cell stack flight test battery).

A. Thermal Cell Stack Construction Detail				
Component (Number of Components Used)	**Individual Mass (g)**	**Total Mass (g)**	**Individual Thickness (mm)**	**Total Volume (cc) /Mass (g)**
Heat pellet (10)	0.742	7.420	0.6198	1.767 cc
A Pellet (9)	0.262	2.358	0.6092	1.563 cc
E/C Pellet (9)	0.667 (0.222 g E and 0.445 g C)	6.003	0.7345	1.884 cc
SS Electrode (17)	0.171	2.907	0.0762	0.3692 cc
B. Battery Construction Detail				
Total internal measured void volume				12.71 cc
Total internal battery case volume (Includes 0.015 in. thick header liner)	Internal Length = 1.409–0.125–0.031 = 1.253 in. = Total length – 0.125 in. thick header – 0.031 in. thick can bottom	Internal Diameter = 1.312–2x0.031 = 1.250 in. = Outer diameter – two can wall thicknesses		25.20 cc

Table 1. LCCM thermal battery characteristics (enhanced 307 A–s capacity thermal cell stack flight test battery) (continued).

Component (Number of Components Used)	Individual Mass (g)	Total Mass (g)	Individual Thickness (mm)	Total Volume (cc) /Mass (g)
Total battery thermal and electrical insulation mass				11.129 g
Total heat paper mass				2.821 g
Total battery flight case and lead wire mass				44.566 g
Total battery mass (measured in welded flight case)				77.204 g (Total mass does not include inertial starter or starter housing.)
C. Chemical Compositions of Thermal Cells (Weight %)				
Heat pellet is $Fe/KClO_4$ (84/16) Delivers 298 cal/g of $Fe/KClO_4$ powder				
E/C Pellet is Electrolyte-Cathode (34/66) double layer pellet				
E is MgO/LiBr–LiCl–LiF eutectic (47/53)				
C is FeS_2/Fe/E (78/2/20)				
A is Li/Al alloy (20/80)/LiBr–LiCl–LiF eutectic (90/10)				
SS is type 304 stainless steel				
Heat Paper is Zr/BaCrO4 powder (28/72?) with glass fiber binder (powder/binder ratio (90/10?))				

D. Thermal Insulation, Electrical Insulation, and Epoxy Vendors	
Min-k Blanket and Molded Sheet	3M Corporation, Elkhart IN 46516
Microtherm Sheet	Microtherm Inc., Alcoa TN 37701
AR5401 Flexible Blanket	Aspen Aerogels, Inc. Northborough MA 01532
Columbia-Glas Tape (non-adhesive) Style ECC11B	Mutual Industries, Red Hill Pa 18076
Electrical Adhesive Glass Tape Scotch #69	3M Corporation
Kapton Electrical Tape Scotch #92	3M Corporation
Fiberfrax 970 F 0.0625 in. thick	Carborundum Co., Niagara Falls NY 14302
muscovite mica	Spruce Pine Mica Co., Spruce Pine NC 28777
E-20NS Epoxy	Henkel North America

E. Energy and Power Densities (Flight Test Battery – values do not include inertial igniter)			
11 to 16 V at 1.5 A for 113 s			
Entire Battery		Electrochemical-Heat Source System	
Wh/l	20.36	Wh/l	114.3
Wh/kg	8.233	Wh/kg	34.33
KW/l	0.6487	KW/l	3.641
KW/Kg	0.2623	KW/Kg	1.094
7.56 to 10.08 V at 11 A for 27.80 s			
Wh/l	24.00	Wh/l	134.7
Wh/kg	9.704	Wh/kg	40.46
KW/l	3.108	KW/l	17.45
KW/Kg	1.257	KW/Kg	5.239

Heat transfer considerations are presently major limiting factors in LCCM thermal battery lifetimes because of the limited space for thermal insulation and because of the need for

mechanically strong thermal insulation materials. High transient state heat loss rates from the thermal cell stack, combined with the significant amounts of heat required to establish steady state temperature gradients in the thermal insulation, are a major problem early in the lifetime of the LCCM thermal battery and affect the maximum temperatures reached by the thermal cells when the batteries are initiated. During most of the LCCM operating lifetime, after a steady state temperature gradient has been closely approached in the thermal insulation, mechanically strong, high density thermal insulators tend to have higher steady state heat loss rates than other insulating materials.

The primary ATO objective was to increase the lifetime of the LCCM thermal battery from the benchmark value of ~90 s to 11 V at a constant current of 1.5 A without changing the external dimensions. Alternative objectives to increase the volumetric energy density of the battery by increasing the current drawn above 1.5 A, and by reducing the outer case dimensions had been accomplished previously (*3*). A major emphasis of the present study was placed on gas gettering and on operating gas atmosphere control methods. These gas control methods showed great promise but have not yet been incorporated effectively into operating thermal batteries. This study also showed that significant improvement was available by controlling heat generating reactions that naturally occur in normally operating thermal batteries. LCCM thermal lifetimes for batteries operating normally in a fore pump vacuum (~7 Pa) were extended to more than 300 s from heat generating reactions associated with increased axial operating stack forces and with elevated operating thermal cell temperatures. Localized overheating of the positive end thermal insulation might have contributed significantly to the initiation and maintenance of the heat generating reactions (compare GPS9N, GPS9P, and GPS9I in table 2). The experiments and calculations in this study confirmed previous results showing that submunition thermal batteries 6 mm tall by 5 mm diameter could be made to operate for approximately 10 min (*4*).

Table 2. Thumbnail chronological sketch of LCCM thermal battery tests.

Battery and Test Date	**Description (Ambient Temperature of Test)**	**Time to 11 Volt at 1.5 A (s)**	**Maximum Measured Time to 430 °C (s)**
Operating axial stack forces were not measured and contribute to electrochemical and thermal lifetimes.			
GPS9F 01/03/07	Benchmark (–40 ºC) Sealed in dry room air at –40 ºC ambient temperature and one atmosphere of pressure and then initiated	83.0 Three end heat pellets – Min-K blanket side wall with molded Min-K axial thermal insulation	50.6
GPS9G 02/14/07	Benchmark (–40 ºC) Sealed in dry room air at –40 ºC ambient temperature and one atmosphere of pressure and then initiated	88.3 Four end heat pellets – Min-K blanket side wall with molded Min-K axial thermal insulation	74.0
Batteries GPS9H through GPS9P were all tested in a fore pump vacuum at ~7 Pa			

Table 2. Thumbnail chronological sketch of LCCM thermal battery tests (continued).

Battery And Test Date	Description (Ambient temperature Of Test)	Time to 11 Volt at 1.5 A (s)	Maximum Measured Time to 430 °C (s)
GPS9H 02/28/07	Last benchmark battery Identical to GPS9F (–40 ºC)	91.9 Min-K blanket side wall with molded Min-K axial thermal insulation – All batteries after GPS9H used heated Microtherm side wall and axial thermal insulation	90.9
GPS9I 04/27/07	All batteries after GPS9H used six silicone rubber gaskets to form a hermetic seal. The silicone rubber gaskets that are not designated as blank had a 1.25 in. diameter center hole removed to reduce the operating thermal cell stack force. (–40 ºC)	143.22 Six blank silicone rubber gaskets for high working stack force – increased measured thermal cell heat generation –2 end heat pellets	348.4 (Top)
GPS9J 05/22/07	Double cathodes (–40 ºC)	Instrumentation problem with voltage (3 blank silicone rubber gaskets one heat paper end heat top)	119.8
GPS9K 06/07/07	Double cathodes (–40 ºC)	168.49 (3 blank silicone rubber gaskets, one heat pellet, one heat paper end heat)	152.3
13 June 2007 Review for Karen Amabile of Picatinny/ARDEC			
GPS9L 06/25/07	~300 A–s Anodes and cathodes (Thinner anodes than used above apparently increased heat generation rates (–40 ºC))	63.08 Burned up – GPS9I gaskets, 2 heat pellet end heat	425.2 (Bottom)
GPS9M 07/11/07	GPS9L anodes and cathodes (–40 ºC)	110.8 GPS9K gaskets, 2 heat paper end heat	292.8 (Top)
GPS9N 07/30/07	307 A–s cathodes, 459 A–s anodes ~ GPS9K anodes, 0.262 g anode, 0.222g separator, 0.445 g cathode, 0.742 g heat pellet (–40 ºC)	142.66 Five blank silicone rubber gaskets, one heat paper end heat - calculated Tpeak 620.975 °C from +60 °C	106.2 (Bottom)
GPS9O 10/25/07	GPS9N cell stack with increased stack force – Late firing heat pellet apparently caused failure (–40 ºC)	50 Burned up – GPS9I gaskets, 2 heat paper end heat	604.1 (Top)
GPS9P 11/13/07	GPS9N cell stack with slightly less dense cell stack heat pellets. Tested in fore pump vacuum (–40 ºC)	176.86 GPS9N gaskets, one heat paper end heat. Evolved 72.4 std-atm-cc gas that was 78.2% H_2 by volume (5.10 mg H_2 gas) during first 10 s	297.78 (Bottom)

Table 2. Thumbnail chronological sketch of LCCM thermal battery tests (continued).

Battery and Test Date	**Description (Ambient Temperature of Test)**	**Time to 11 Volt at 1.5 A (s)**	**Maximum Measured Time to 430 ° C (s)**
The GPS9Q cell stack cooled 2.87 times faster than the GPS9P cell stack between 200 and 100 ºC.			
GPS9Q 12/10/07	Construction identical to GPS9P. Sealed in dry room air at –40 ºC ambient temperature and one atmosphere of pressure and then initiated. Gas collected at –40 ºC only after temperature-time measurements were complete (1480.4 s after battery initiation)	99.36 Operating gas pressure was 1.08 MPa (~10.7 atm) calculated from the final measured volume of 88.4 std-atm-cc of gas that was 56.2% by volume hydrogen (4.47 mg H_2 gas)	154.305 (Bottom)
Battery GPS9R contained gas getter and was hermetically sealed with dry room air at one atmosphere of pressure at –40 ºC before initiation. No gas was withdrawn until after the test was complete. The GPS9R/GPS9Q cell stack cooling ratio between 200 and 100 ºC was 1.00015. Subsequent GC analyses also showed that the gas getter was ineffective.			
GPS9R 01/24/08	Cell stack identical to GPS9P (–40 ºC)	95.985	144.54 (Top)
GPS9S 02/13/08	Cell stack identical to GPS9P. Built into RTF. Sealed containing dry room air at –40 ºC and 1 atmosphere pressure before ignition. Thin Microtherm side wrap next to cell stack. No pre-compression of any side wall insulation or side wall heat paper (–40 ºC)	112.872 GPS9K gaskets – Reduced stack force to simulate anticipated field test conditions – Extra heat paper side wrap near outer case	97.227 (Bottom)
GPS9T 02/27/08	Internal construction identical to GPS9S. Built into flight case as identically as possible to GPS9S. Laser-welded closed under one atmosphere of dry room air at room temperature and ~170 lb stack force. Tested at room temperature (~ +21 ºC)	168.528 Normal thermal battery stack pressure of ~400 lb/in.^{2} – Only Microtherm supplied spring action in operating battery – Postmortem leak rate was 2.5E-7 std-atm –cc He/s. Maximum case temperature at bottom was 267.801 °C at 25.662 s	No thermocouples were attached to the thermal cell stack.
Copper–Heat Pellet Stack 03/20/08	Thermal insulation package identical to GPS9P and GPS9Q. The copper–heat pellet stack geometry was built as identical as possible to that of the GPS9P and GPS9Q thermal cell stacks. This heat transfer experiment was initiated, the gas sample was collected, and the test fixture was evacuated using a mechanical fore pump all with within ~10 s after initiation (–40 ºC)	The gas sample evolved during the first ~10 s of experiment occupied 49.7 std-atm-cc and was 76.0% by volume H_2 (3.40 mg H_2 gas)	130.101 (Center)

Battery construction methods and thermal optimization programs written for LCCM thermal batteries in Fortran are shown in the appendices. Fortran programs are identified as they appear in archived ARL electronic files for future reference. Numerous comment statements have been included within the Fortran programs. Some of the more recently added comment statements have been removed for this report in the interest of brevity but remain available on the archived ARL electronic files. Numerical constants are typically maintained to six significant figures throughout this report to aid in debugging of the Fortran programs. The estimated accuracy of critical numerical constants is reported along with explanations of the calculations. Significant insights into the effects and interrelationships of the Fortran program input parameters on thermal battery lifetimes can be achieved by a careful study of the Fortran programs in the appendices.

A search for novel thermal insulators showed that the control of gas atmospheres in existing micro-porous or multifoil thermal insulators is presently the most effective method of reducing heat losses. Special-order thin, low density, micro-porous thermal insulation—especially effective for side wall heating applications—was obtained from Microtherm and was used in the flight test batteries. Aspen Aerogel supplied a micro-porous thermal insulator that apparently adsorbed H_2 gas quickly, and that might be useful early in battery life before getter materials have become fully activated.

2. Experimental

All pyrotechnically and electrochemically active chemical components were purchased commercially and then processed for use at ARL in a dry room with the nominal dew point at –56 ºC (0.074% relative humidity at 70 ºF). All batteries were assembled in the same dry room. The thermal cell active stack had a 19.05 mm (0.75 in.) diameter with no center hole. The RTF inner dimensions were made as closely as possible to those of the flight cases after allowing for a flight case battery header liner 0.015 in. thick. The measured RTF inner diameter was 31.64 mm (1.246 in.) and the measured RTF inner length was 31.45 mm (1.238 in.). The RTF was machined from type 316 stainless steel (SS) and weighed nominally 1300.5 g. The RTF lid was nominally 2.67 in. diameter x 0.325 in. thick type 316 SS and weighed 232.2 g. Ignition was accomplished with a heat paper fuse strip. A target value of ~400 lb/in.^{2} was used for the axial closing pressure of the laboratory and flight test batteries, and for the radial side wall wrapping pressures.

The hermetic gas seals for the laboratory batteries were obtained by using silicone rubber or a combination of silicone rubber and Viton gaskets between the RTF case and lid. SS Allen cap screws were used to attach the RTF case and lid. The screws were tightened by hand with a regular Allen wrench and no vacuum grease was used on the gaskets. This provided an acceptable and easily formed hermetic gas seal and reduced construction time requirements.

With the RTF at –40 ºC, a typical test of this hermetic seal using argon (GPS9J) showed that the system gas pressure decreased from 7.54 atm to 7.42 atm in 14 h and 13 min.

Initial voltage spikes over 16 V were permitted for this application, but those can be eliminated by altering the chemical processing methods. Most batteries were tested at –40 ºC because the shortest lifetimes occur when the batteries are discharged at –40 ºC. All of the batteries were designed to operate at a spin rate of 300 Hz over an ambient temperature range of –40 ºC to +60 ºC.

Battery, thermocouple, and gas pressure transducer voltages were measured using a Maccor Model 4300 battery tester. Batteries were discharged at a constant current of 1.5 A with 10 ms pulses of 0.5 A at 10 s intervals to measure the battery internal resistances. Thermocouple temperatures were measured using an Agilent 34970A Data Acquisition/Switch Unit. Three to six type K 30 American wire gauge thermocouples (0.010 in. diameter wires) were used depending on experimental requirements.

The thermocouple wire ends used to form the thermocouple junctions at the thermal cell stack ends were first flattened to a nominal thickness of 0.005 in. between hardened steel pieces. The flattened portions of the positive and negative thermocouple wires were then spot-welded individually to one of the 0.75 in. diameter by 0.003 in. thick type 304 SS disk cell covers. The two thermocouple wires forming the junctions on the SS disks did not make direct contact with each other so that the thermocouple junctions in the thermal cell stacks all included a portion of the SS disk. The electrical leads were all type 304 SS ribbons, nominally 0.10 in. wide by 0.003 in. thick, that were spot-welded to the same SS disks as the thermocouple wires. During battery construction, the SS thermocouple/electrical lead disks were placed on the extreme outer ends (top and bottom) of the thermal cell stacks. The thermocouple wires and SS lead ribbons were all spot-welded to the sides of the SS disks facing the thermal insulation and were all electrically insulated with glass spaghetti, mica, and #69 Scotch electrical tape (see appendices A, B, and C for battery construction details).

Chemical compositions of the operating gas atmospheres were measured using an HP 5890 Series II Gas Chromatograph (GC) as previously reported (*5*). Internal operating gas pressures were measured using MKS Baratron pressure sensors with output voltages ranging from 0 to 10 V and full scale readings ranging from 1000 to 25000 torr (133 kPa to 3.33 MPa). The Baratron pressure accuracy ratings were either 0.5% or 1.0%. A Bourdon gauge was attached to the gas collection system as a rough check of the transducer gas pressure readings. Gas pressure readings as low as 3 Pa were confirmed with a mercury McLeod gauge. Hermetic seals for the flight test batteries were confirmed using an Adixen ASM.142 helium leak tester.

3. LCCM Development Overview

For convenience, some measured and target value construction and operating characteristics of hardware-proven LCCM ATO thermal batteries are summarized in table 1; these batteries used the enhanced 307 A–s capacity thermal cell stack that was used in the flight test batteries. The internal construction of a typical benchmark thermal battery (GPS9G with 194 A–s electrochemical capacity) that delivered 88.3 s to 11 V under a constant current drain of 1.5 A at an ambient temperature of –40 ºC in the heavy heat sink RTF test fixture is shown in detail and explained briefly in appendix A.

The benchmark thermal batteries used Min-k blanket side wall and end thermal insulation with no side wall heat paper to heat the Min-k blanket and used heat pellets to grossly overheat the end thermal insulation. Although the median temperature of the thermal insulation during battery operation is nominally 300 ºC, portions of the thermal insulation can be heated momentarily to the maximum operating temperature of the thermal cells (nominally 620 ºC) without damage to the insulation or thermal cells. The excess heat supplied in this way contributes to a small increase of the battery lifetime. Most of the excess heat from the end heat pellets will, however, be lost quickly into the battery case. The use of excess heat in the thermal insulation helps to insure that significant amounts of heat will not be lost from the thermal cells into the thermal insulation during the transient heat transfer state immediately after battery initiation. The excess heat must, of course, be added to the package in such a manner that the thermal cells will not be overheated.

Electrical lifetimes in excess of the time for the cell stack to cool to the electrolyte freezing point of ~430 ºC were observed for some batteries, including GPS9G. This is possible because of the placement of the thermocouples at the very ends of the battery stacks, and because of the low thermal conductivity and high current capability of the molten salt electrolyte.

A thumbnail chronological sketch of LCCM development tests for the ATO is shown in table 2. After the LCCM benchmark performance was demonstrated, an LCCM thermal battery with an enhanced 307 A–s capacity electrochemical cell stack was developed using the RTF with a Microtherm/heat paper side wrap thermal insulation package. The same enhanced 307 A–s electrochemical capacity thermal cell stack was used for batteries GPS9N and for all batteries constructed after GPS9N, including the flight test batteries that were supplied to Picatinny/ARDEC. The heat pellets of GPS9G in the 19.05 mm diameter end thermal insulator disks directly above and below the thermal cell stacks were replaced with heat paper disks that delivered smaller amounts of heat to the end thermal insulation for GPS9N and subsequent batteries. GPS9N and subsequent batteries used the heat paper in the side wall insulation/heat paper wrap to heat substantial portions of the end thermal insulation. The internal construction

detail of an enhanced 307 A–s capacity battery built into the RTF (GPS9Q) is described in appendix B.

Several heat transfer optimization techniques were investigated experimentally including: (1) control of the operating gas atmospheres by fore pump evacuation, (2) increased operating thermal cell heat generation achieved by increasing axial stack forces and by reducing anode pellet thicknesses, and (3) independent pyrotechnic heating of the side wall and end thermal insulation to reduce initial transient state heat loss rates from the thermal cells into the thermal insulation. Heat pellets were used only in the thermal cell stacks (ten heat pellets with nine thermal cells) for all of the enhanced 307 A–s capacity batteries built after GPS9L in table 2. Heat paper was used in both the side and end thermal insulation, and was the only pyrotechnic material placed in the thermal insulation for all of the batteries built after GPS9L.

Batteries GPS9I through GPS9R used two Microtherm 2 mm thick side wall thermal insulators pre–compressed at nominally 1500 lb/in.^{2} and used uncompressed heat paper sandwiched between them to heat the Microtherm side wraps. It was necessary to pre–compress the Microtherm side wrap material so that the wrapped stack could be inserted into the RTF. The heat paper could not be pre–compressed separately because it became too fragile to wrap easily. The heat paper could not be pre–compressed between the Microtherm side wraps because it blended with the Microtherm, which made reliable ignition questionable.

An improved flight test version (GPS9S) of the LCCM thermal battery using the enhanced 307 A–s capacity thermal cell stack was then built into the RTF. The internal construction of a representative flight test version LCCM battery (GPS9T) is described in appendix C. All of the internal axial components of GPS9S and GPS9T were constructed as identically as possible. The flight test batteries used one 1 mm (inner) and one 2 mm thick (outer) Microtherm side wall thermal insulator with two heat paper wraps to heat the Microtherm side wall thermal insulation. One heat paper wrap was placed between the two Microtherm wraps, and one heat paper wrap was placed near the flight case inner diameter. The thin Microtherm side wrap was placed next to the cell stack in order to minimize heat flow into that side wrap under transient heat transfer conditions immediately after battery initiation. For the flight test batteries, neither the side wall thermal insulation nor the heat paper was pre–compressed.

GPS9S and GPS9T were both initiated electrically and tested at ARL under laboratory conditions. GPS9S was built into the RTF heavy metal heat sink and delivered 112.9 s under the benchmark battery test conditions in the heavy metal RTF heat sink at an ambient temperature of –40 ºC. GPS9T was built into a laser-welded flight case and delivered 168.5 s under the same electrical requirements at an ambient temperature of +21 ºC in the absence of external heat sinks (table 2). The GPS9T flight test battery had no inertial starter or starter housing attached to the flight case and had thermocouples attached to the external flight case but not to the internal thermal battery components.

All of the batteries shown in table 2 except for GPS9T were tested at an ambient temperature of –40 ºC. All of the batteries shown in table 2 were designed to operate over the ambient temperature range –40º C to +60 ºC. A flight test battery using the enhanced 307 A–s capacity thermal cell stack and built as identically as possible to GPS9T—but that included the inertial igniter—was potted in epoxy and successfully delivered ~169 s to 11 V at room temperature across a 10 Ω load, as measured by telemetry in an air gun at Picatinny/ARDEC. A total of six flight test batteries, all built as identically as possible to GPS9T—except that they included inertial igniters—were shipped to Picatinny/ARDEC for air gun testing and for flight testing in the 155 mm howitzer (figure 1).

Figure 1. LCCM thermal batteries used in flight tests at Picatinny/ARDEC.

4. Battery Assembly and Test Procedures

The battery cell stack components and the axial thermal insulators and pyrotechnic components were assembled onto a 0.75 in. diameter steel rod within a stacking fixture (figure 2) to assure proper alignment. A force ranging from 170 to 200 lb was then applied to the cell stack top using a second 0.75 in. diameter steel rod. Pellet chips that resulted from the application of the 170 to 200 lb stack force were removed carefully using Accuwipes, magnets, forceps, and a vacuum cleaner. Most of the chips removed came from the magnetic pyrotechnic pellets, but a significant amount of chips came from both the anode and from the electrolyte-cathode pellets. The presence of anodic chips was confirmed visibly by observing the reactions of those chips with water. Pellet chips that result from the initial pressing of thermal cell stacks can be caused by edges on the pressed powder pellets that result from worn pellet die edges or poor die tolerances, and also by pellet dies with faces that are not parallel, so that wedge-shaped pellets are formed.

The amount of pellet chip material formed during this step can be reduced significantly by the proper choices of the pellet die maintenance and tolerances, pellet densities, materials selection, pellet pressing techniques, and powder processing methods.

Figure 2. LCCM cell stack alignment fixture.

The fuse strip and the Fiberfrax side wrap were then added and held in place with glass adhesive tape. Some adhesive was required to facilitate construction, but the use of adhesives on the glass tapes was minimized to reduce gas evolution following ignition of the pyrotechnic materials. Glass tapes with no adhesives were used whenever possible. Fiberfrax was wrapped and held tightly against the cell stack diameter using glass tapes with and without adhesives. Wrapping pressures were not measured but were believed to be similar to those required to close the header (~400 lb/in.^{2}). The various wrapping sequences for the batteries are discussed briefly in appendices A through C. To begin the outer wrap of the thermal insulation and heat paper, for example, two short glass adhesive tape strips were first taped firmly to either end of a much

longer non-adhesive glass tape strip. One of the short glass adhesive tape ends was then taped firmly to the cell stack outer diameter, which was already covered with non-adhesive glass tape from a previous wrapping process. All of the remaining thermal insulation and heat paper side wrap layers were then assembled in sequence and taped in place simultaneously using ~400 lb/in.^{2} pressure on the long non-adhesive glass tape strip. The resulting wrap was held in place temporarily using the second short end adhesive tape strip. The entire outer diameter was then tightly wrapped using ~400 lb/in.^{2} pressure with a single layer of glass adhesive tape for mechanical integrity during assembly. Cell stack and side wrap heat paper fuse train continuity for ignition of all of the enhanced 307 A–s capacity thermal cell stack batteries was assured by using a flat heat paper disk to cover the entire case end directly under the inertial igniter. The cell stack fuse train and the side wall heat paper wraps were both exposed at the igniter end of the side wrap assembly in order to contact the igniter end heat paper disk directly. The amount of heat paper overlap at the positive end of the Microtherm–heat paper side wrap was difficult to control and might have contributed to the differences in the stack bottom temperatures for GPS9N and GPS9P, as noted above (table 2) and discussed below. Electrically initiated batteries were ignited at the header end of the battery using a 0.003 in. diameter nichrome wire with a 2000 μF capacitor charged to 85 V. The benchmark thermal batteries used only electrical initiation and did not use any side wrap heat paper or flat heat paper disk at the igniter end of the case.

Most of the batteries were built into the heavy RTF steel heat sink shown in figure 3. The measured temperatures of the heavy (1300.5 + 232.2 g) type 316 SS RTF case and lid did not change greatly from ambient temperatures when the batteries were tested so that the test conditions approached worst case heat sink conditions. The RTF was hermetically sealed using silicone rubber gaskets for ease of construction during laboratory testing. Spring action from the silicone rubber gaskets applied significant stack force to the ends of the thermal cell stacks and appeared to have surprisingly significant effects on the thermal cell heat generation rates and amounts, as can be seen in table 2. The increased heat generating reactions observed did not, however, decrease the electrochemical lifetimes of the batteries significantly when the anode and cathode thicknesses were as large as those used for the flight test batteries (table 2).

Field test batteries in light flight cases used battery headers laser-welded to 304 SS cans. Inertial igniter housings were laser-welded and/or silver-brazed to the SS cans externally, and were hermetically sealed using E–20NS high temperature epoxy. The hermetic seals were confirmed to better than 10^{-5} std-atm-cc He/s using the helium leak tester. The total mass of a hermetically sealed field test battery was approximately 96 g with, and approximately 77 g without, an inertial igniter and housing attached to the flight case.

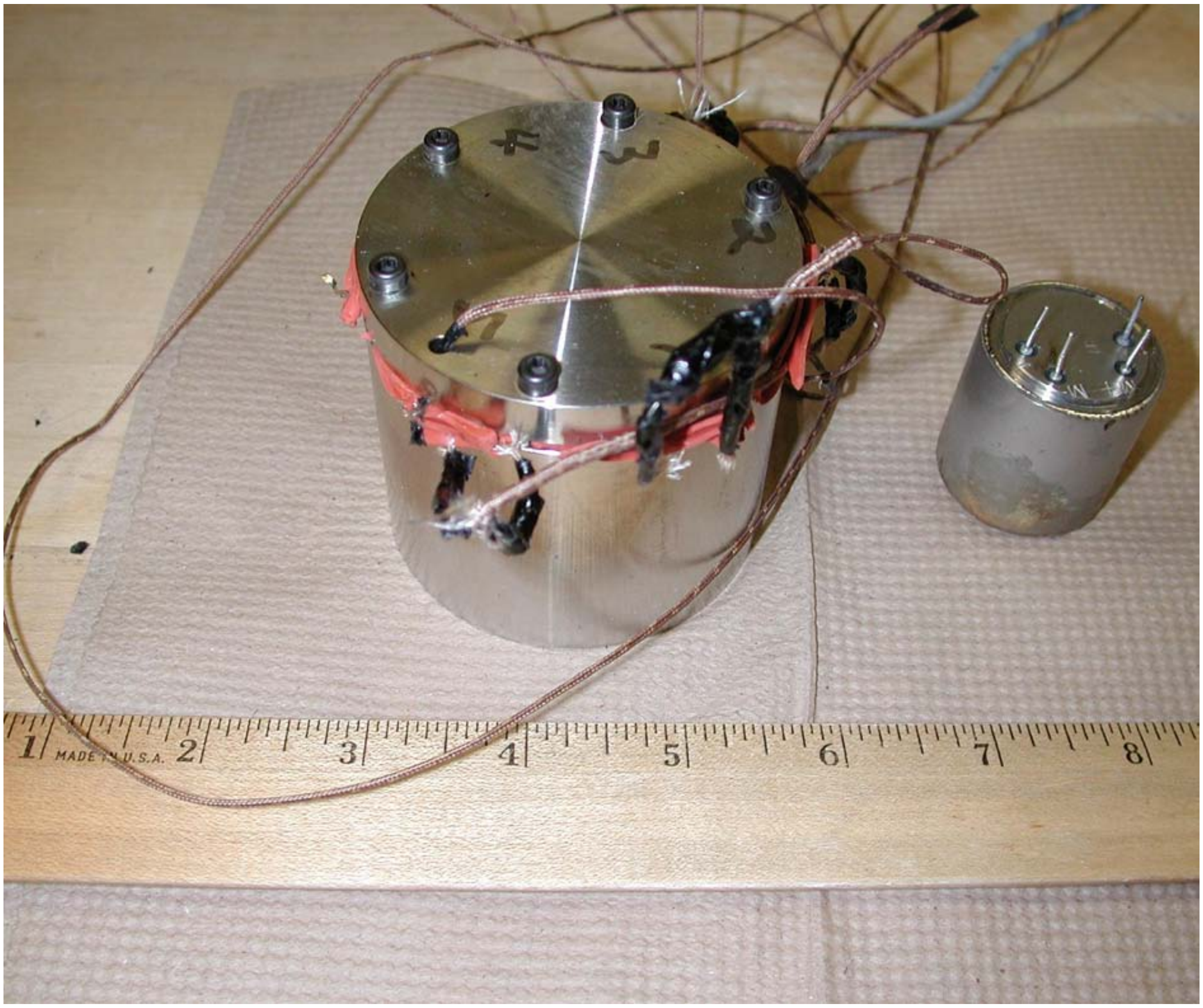

Figure 3. RTF assembly shown with silicone rubber hermetic seals and gas collection system (copper tubing) attached—flight case battery without inertial starter housing to right.

The gas collection system is shown with a 10 cc SS sample bottle in front and a pressure transducer attached at the far right in figure 4. The copper inlet tube from the RTF can be seen attached near the Bourdon gauge in the rear. The Bourdon gauge was used as a rough verification of the transducer gas pressure readings. To check for H_2 gas contamination from previous gas samples, the entire gas collection system with the 10 cc sample bottle, but excluding the RTF, was filled with ultra pure carrier grade H_2 gas at 9.11 atm pressure for 46 h and 15 min, and was then flushed with dry room air at a pressure of one atmosphere six times using a fore pump vacuum of ~7 Pa over a 25 min period. The sample bottle and gas collection system excluding the RTF were then filled with dry room air at a pressure of one atmosphere and the sample bottle was closed for analysis. The GC analysis showed 4.99% by volume H_2 gas in the sample bottle at one atmosphere of pressure. The gas collection system plus sample bottle volume was 25.9 std cc at one atmosphere of gas pressure, which corresponds to 0.116 mg of

residual H_2 gas in the gas collection system plus sample bottle, which is negligible when compared with the 4.47 mg of H_2 gas that was found for the GPS9Q thermal battery.

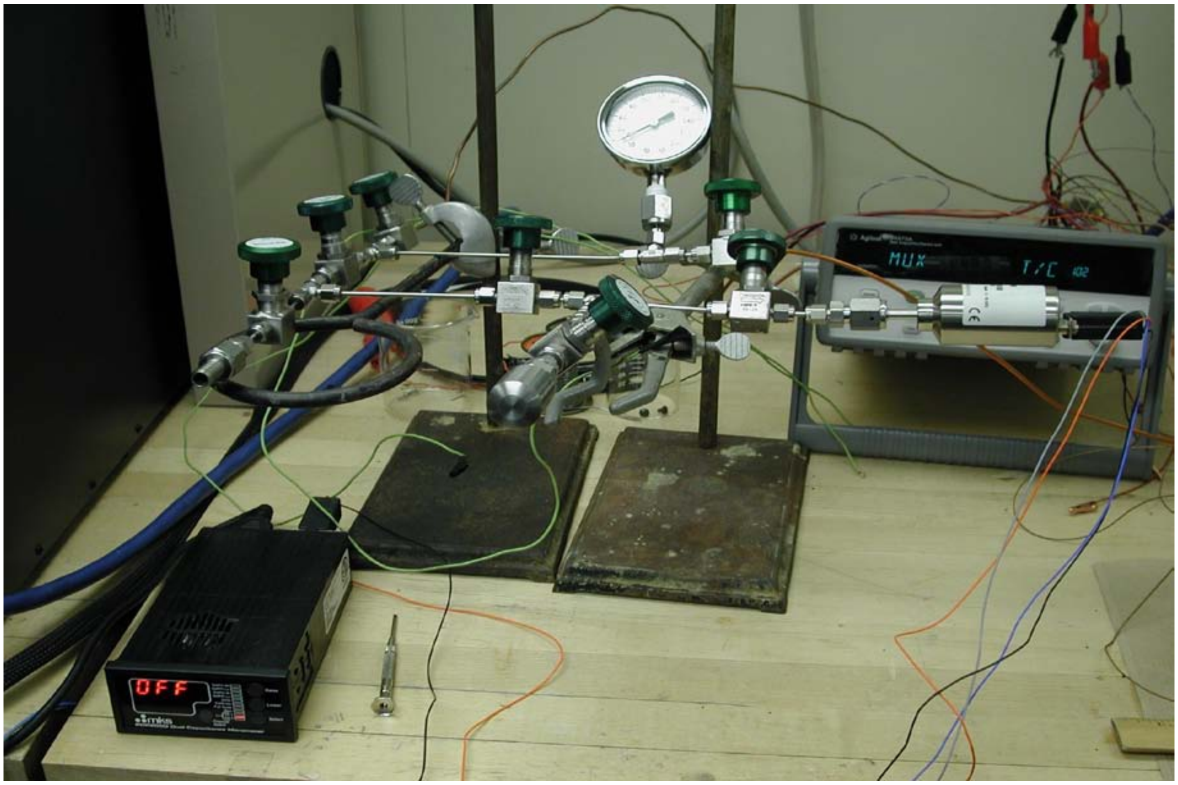

Figure 4. LCCM gas collection system.

5. LCCM Fortran Thermal Optimization Programs and Experimental Temperature-Time Curves

Fortran programs shown in this report are all identified by name and date and are archived at ARL for future reference. Much of the original Fortran programming was done in Fortran 77 and in versions previous to Fortran 77. After 13 January 2009, an updated Fortran compiler (compatible with Fortran 77, Fortran 95, and Fortran 2003) was used. The updated compiler produced the same numerical answers as the previous compiler when using the same numerical input values, but the output printout formats for identical programs were sometimes slightly different. The optimization program shown in appendix D was written using the new compiler and is compatible with improved calculation techniques that are planned for use with the Major Shared Resource Center in Aberdeen, MD, in the near future. Some rewriting of the original

Fortran code was necessary. Updated Fortran program versions and their compilers are generally designed to be backwards compatible with previous Fortran versions in order to reduce the amount of rewriting required for legacy programs.

Fortran programs used to thermally optimize the enhanced 307 A–s capacity thermal cell stack battery, and to determine the heat balances and chemical compositions for the thermal cells, are shown and explained briefly in appendix D. Many thermal reserve batteries use thermal insulation masses that are small with respect to the thermal masses of the cell stacks. The required amount of heat pellet material to heat the thermal insulation can then be calculated directly from the optimization program in appendix D by using appropriate thermal insulation heat capacity values (expressed in terms of cal/cm^3 in the output files). Heat pellets that are larger than what is necessary can be used to heat the thermal cells, and the excess heat can then be used to heat the thermal insulation. Because the mechanically strong thermal insulation required for LCCM is massive (both thick and dense), auxiliary heating of the thermal insulation by heat paper was necessary, as explained in appendix D. The basic heat transfer calculation methods have been discussed previously (*1*–*9*).

The thermal conductivity values used in the thermal optimization files of appendices D–1 through D–3 are brochure thermal conductivity values for Microtherm with 60/40 volume percent H_2/N_2 gas mixtures at one atmosphere of pressure filling the porous Microtherm structure. As can be seen in appendices A through C, the thermal insulation package contained significant amounts of electrical and thermal insulation other than Microtherm. The measured thermal lifetime of the GPS9S flight test battery when initiated at –40 ºC in the RTF was 97.3 s, far less than the calculated 362.7 s thermal lifetime shown in the output file of appendix D–3. The Fortran optimization program shown in appendix D–2 establishes the required internal heat balances and calculates the thermal lifetimes from the thermal conductivity values supplied. Measured cooling curves for the thermal cell stack can be used to calculate experimental thermal conductivity values for the thermal insulation packages during battery operation, as explained in section 6 and appendix E.

Appendix D–4 shows the calculation of an individual thermal cell heat balance, appendix D–5 shows the calculation of the chemical composition of the E/C pellet, and appendix D–6 shows the calculation of the thermal cell electrochemical capacity. Experimental temperature-time curves for two identically constructed enhanced 307 A–s capacity LCCM thermal batteries operating in a fore pump vacuum of 7 Pa (GPS9P) and at a pressure of 10.7 atm or 1.08 MPa (GPS9Q) are shown in figure 5. The measured voltage-time and internal resistance-time curves for GPS9P are shown in figure 6.

The Fortran mathematical optimization methods shown in this report have correctly predicted and helped to interpret numerous experimental results, and they are supported by previously reported Excel and ANSYS finite element heat transfer analyses (*7*, *8*). Data taken at low

temperatures, long after the thermal cell electrolyte has frozen and the exothermic thermal cell reactions have stopped, are especially important in confirming the thermal conductivity values of the thermal insulation packages.

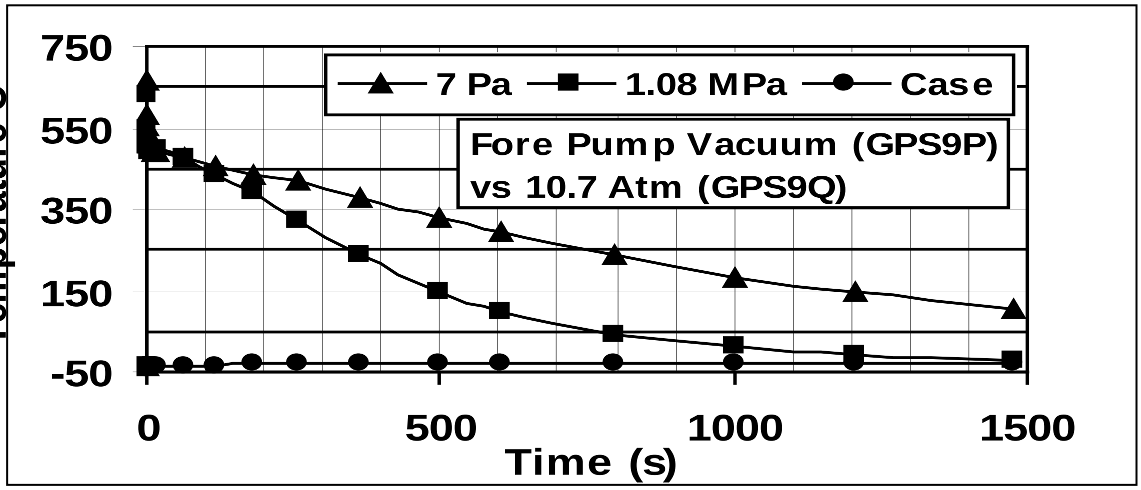

Figure 5. LCCM enhanced 307 A–s thermal battery cooling curves.

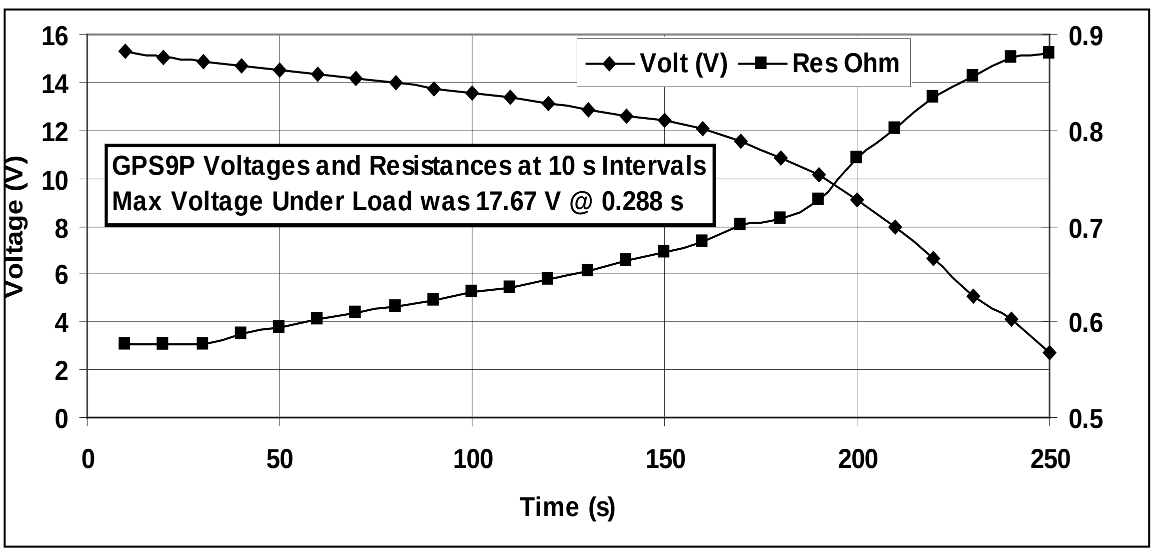

Figure 6. GPS9P LCCM thermal battery voltage and resistance measurements.

6. Thermal Conductivity Values Measured from LCCM Cooling Curves

Small changes in the thermal cell component masses occur from battery to battery, but the thermal cell stacks for batteries GPS9N through GPS9T all used enhanced 307 A–s thermal cell stacks constructed as identically as possible using the output values of the optimization programs

shown in appendix D. The same thermal insulation package was used for thermal batteries GPS9N through GPS9Q. GPS9R used gas getter material in the thermal insulation. GPS9S and GPS9T and the batteries supplied to ARDEC for air gun and flight testing all used enhanced 307 A–s thermal cell stacks with an extra heat paper side wrap near the battery case diameter, and with one thin Microtherm side wrap near the thermal cell stack, as described in appendix C and explained in section 3.

GPS9P operated under a fore pump vacuum of 7 Pa (except for the first ~10 s of the experiment) at –40 ºC ambient temperature and evolved 72.4 std-atm-cc of gas during the first ~10 s of operation that was 78.2% by volume H_2 (5.10 mg H_2 gas). GPS9Q, built as identically as possible to GPS9P, was sealed at –40 ºC and then initiated while containing 1 atmosphere of dry room air at –40 ºC. GPS9Q operated at approximately 1.08 MPa (~10.7 atm) and contained 88.4 std-atm-cc of gas at the end of the experiment, 1480.4 s after battery initiation, of which 56.2% by volume was hydrogen (4.47 mg H_2 gas). The 10.7 atm operating pressure for GPS9Q was estimated by measuring the amount of gas at the end of the experiment, and calculating the gas pressure that would have resulted from having that 88.4 std-atm-cc of gas confined in the measured combined void volume inside the battery, as well as in gas collection systems up to the bellows valve that sealed the battery (12.71 (table 1)+1.78=14.49 cc) at the effective gas temperature (477.45 K) 60.626 s after battery initiation.

The global experimental thermal conductivity values of the thermal insulation package during battery operation under the estimated operating atmospheric pressure of 10.7 atm (1.08 MPa) were ~3.3 times those of the Microtherm brochure values in an atmosphere of 60/40 H_2/N_2 at one atmosphere of pressure. They were ~2.2 times those of the Microtherm brochure thermal conductivity values in one atmosphere of N_2 when the battery was operating under the fore pump atmospheric pressure of 7 Pa.

The high heat loss rates measured for the thermal insulation packages demonstrate both the effect of H_2 gas composition and the effect of gas pressure on the thermal conductivity of the insulation package. The high measured thermal conductivity values for the thermal insulation package at 7 Pa might have resulted partly from mechanical compression of the Microtherm in the insulation package, and partly from the fact that the insulation package contained significant amounts of thermal (and electrical) insulation other than Microtherm. Fortran programs used to determine the global thermal conductivity values for the LCCM thermal battery insulation package of the GPS9P and GPS9Q thermal batteries (appendix B) from the experimental cooling curves are shown and discussed briefly in appendices E–1 through E–4.

7. Copper–Heat Pellet Stack — Separating Transient Heat Flow and Thermal Cell Heat Generation

When the LCCM thermal battery is first initiated, heat flows rapidly into the thermal insulation and the thermal cells generate significant amounts of heat. These two effects drive the stack temperatures in opposite directions. A simulated LCCM thermal battery using copper in the place of thermal cells was built to separate these two effects. Fortran programs used to determine the copper–heat pellet stack construction parameters, and to use the copper–heat pellet stack cooling curves (figure 7) to calculate apparent global thermal conductivity values for the thermal insulation package after pyrotechnic initiation (figure 8), are shown and explained briefly in appendices F–1 through F–3. An Excel trendline plot for the portions of the copper–heat pellet stack package thermal conductivity experimental values that closely follow a linear relationship is shown in figure 9.

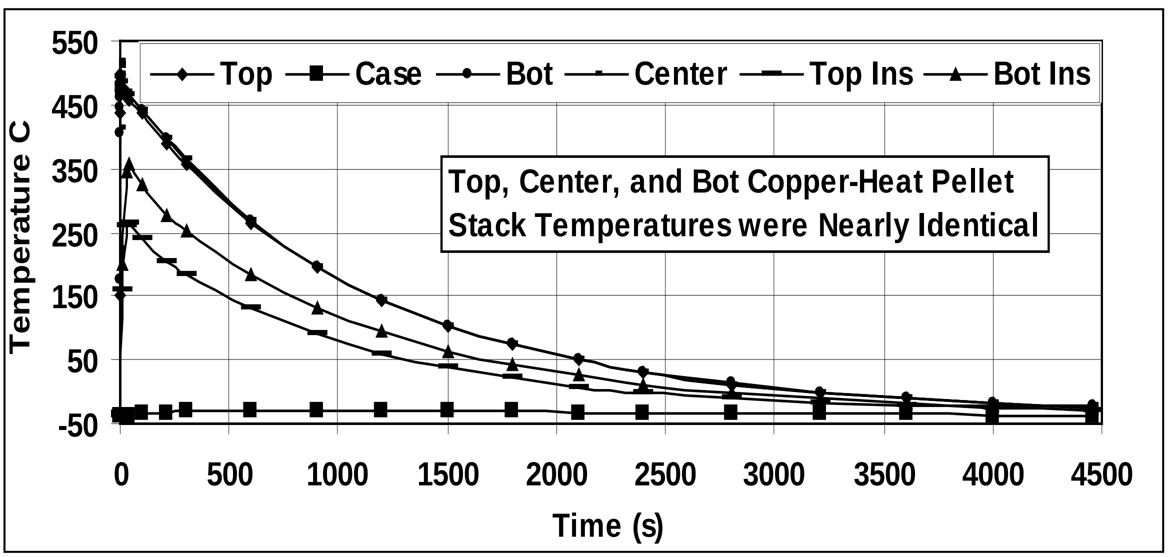

Figure 7. Copper–heat pellet stack cooling curves.

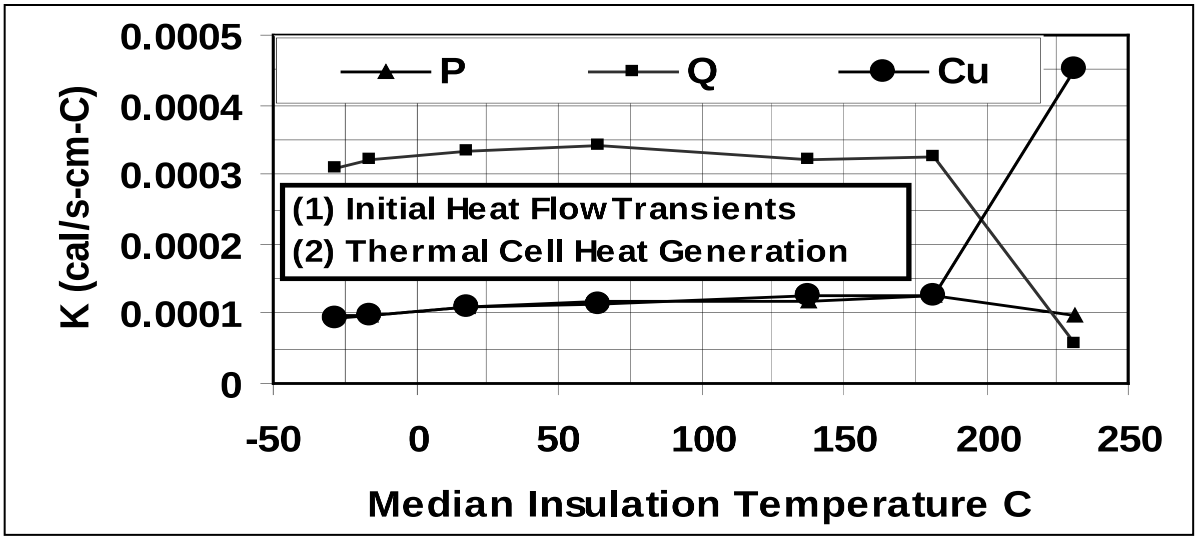

Figure 8. Apparent global thermal insulation package thermal conductivity values from the copper–heat pellet stack cooling curves compared with those from operating LCCM thermal battery cooling curves.

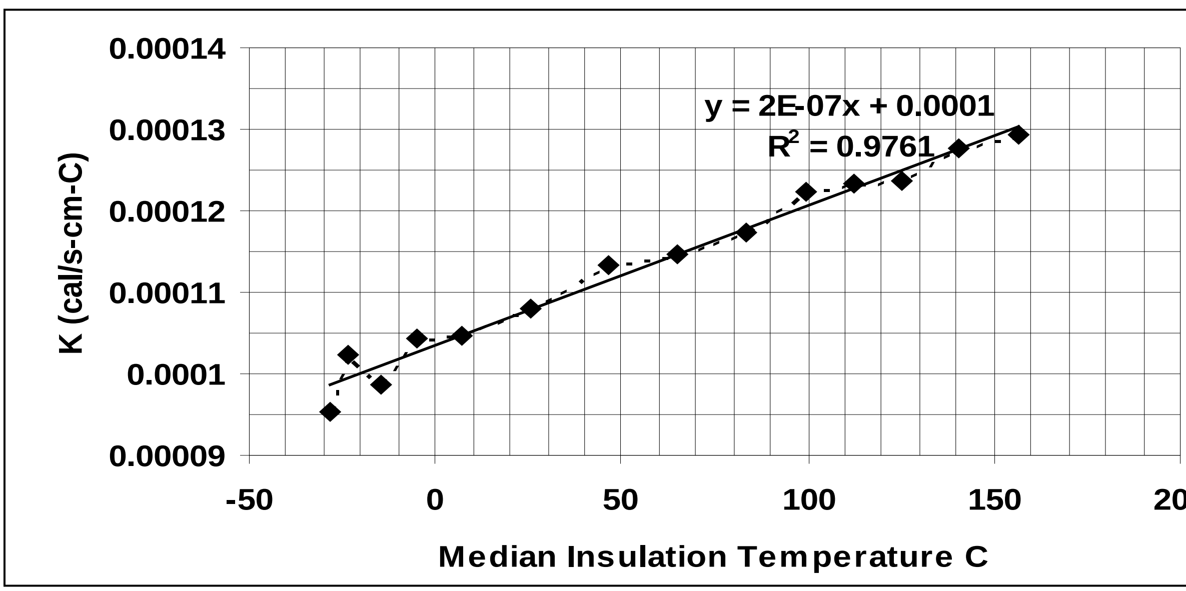

Figure 9. Linear apparent global thermal insulation package thermal conductivity experimental values from the copper–heat pellet stack at 7 Pa gas pressure.

The copper–heat pellet stack was built as closely as possible to the same dimensions as the enhanced 307 A–s capacity LCCM thermal battery stack used in both GPS9P and GPS9Q, and used a thermal insulation package built as identically as possible to that used for both GPS9P and GPS9Q. The heat pellets used in the copper–heat pellet stack were as identical as possible to those of GPS9P and GPS9Q, and the amount of copper used was adjusted so that the copper–heat pellet stack would be heated to temperatures similar to those of the GPS9P and GPS9Q thermal cell stacks when the heat pellets were initiated.

The resulting copper–heat pellet stack contained 12 LCCM heat pellets of total mass 8.853 g, rather than the 10 heat pellets of total mass ~7.42 g contained in the batteries, and used 48 copper disks. Each copper disk was nominally 0.010 in. (0.254 mm) thick, and the total mass of all the copper disks was 30.644 g.

Figure 8 illustrates and compares the apparent thermal conductivity values for the copper–heat pellet stack thermal insulation package calculated from the cooling curves shown in figure 7 with those for the LCCM thermal insulation packages calculated from the LCCM cooling curves of figure 5. The thermal capacity of the copper–heat pellet stack was about 20% greater than that of the enhanced 307 A–s capacity thermal cell stacks (6.06 cal/ºC compared with 4.97 cal/ºC between 60 ºC and 600 ºC, for example). The top, center, and bottom of the copper–heat pellet stack all showed similar temperatures throughout the experiment and are difficult to distinguish from one another in the curves shown in figure 7. Temperatures were measured at points in the top and bottom thermal insulation directly above and below the 0.75 in. diameter stack diameter using type K thermocouples spot-welded to 0.75 in. diameter by 0.003 in. thick 304 SS disks that were separated from the copper–heat pellet stack by a single Microtherm disk of ~0.086 in. uncompressed thickness in order to facilitate analysis of heat transfer in the transient state.

The apparent thermal conductivity values shown in figure 8 assume steady state temperature heat loss rates calculated directly from the cooling curves. The curves in figure 8 do not include the effects of transient heat flow or heat generation from the thermal cells. The high apparent thermal conductivity values for the copper–heat paper stack early in the battery lifetime, therefore, demonstrate the effect of rapid transient heat flow into the dense thermal insulation package during the transient state. The corresponding low apparent thermal conductivity values for the thermal batteries during this same time period demonstrate the rapid heat generation rates from the thermal cells.

The heat pellets of the copper–heat pellet stack were initiated in the hermetically sealed RTF under a fore pump vacuum, and 10 cc of the evolved gas sample was obtained within ~10 s following activation of the pyrotechnic. After collection of the gas sample, the RTF was evacuated to a fore pump vacuum of ~7 Pa for the duration of the experiment. Measurements made on the 10 cc gas sample showed that the copper–heat pellet stack had evolved 49.7 std-atm-cc of gas, which was 76.0% H_2 by volume (3.40 mg H_2). The relatively large amount of H_2 gas formed in the copper–heat pellet stack experiment suggests that much of the H_2 gas that formed in the operating thermal batteries was evolved from the pyrotechnic materials.

8. Copper–Heat Pellet Stack — Alternate Transient Thermal Conductivity Measurement Method in Selected Gas Atmospheres

An understanding of the behavior of the copper–heat pellet stack thermal insulation package is important because it is an effective package for high spin thermal batteries. The package contains both micro-porous and standard thermal insulation geometrically arranged to optimize high spin thermal battery performance, along with electrical insulation and heat paper ash that was used to heat the thermal insulation. The insulation package thermal conductivity values in various gas atmospheres are not available in the literature and are not easily calculated. The package was used with slight variations for all the LCCM batteries built in this study after GPS9M, including the flight test batteries. Alternate transient methods were used to continue the measurements of thermal conductivities of the copper–heat pellet stack experiment thermal insulation package after the initial temperature-time curves shown and discussed previously were obtained and analyzed.

For the alternate transient thermal conductivity experiments, the copper–heat pellet stack RTF was filled with gasses of known composition and then transferred between temperature chambers that were preconditioned to different temperatures. One example of the resulting heating/cooling curves is shown in figure 10. Apparent thermal conductivity values calculated from the figure 10 cooling curves, and from cooling curves similar to those shown in figure 10, are shown in figure 11. The experimental temperature points shown in figure 10 are the points that were chosen for calculation of the thermal conductivity values of figure 11, as explained in appendix G.

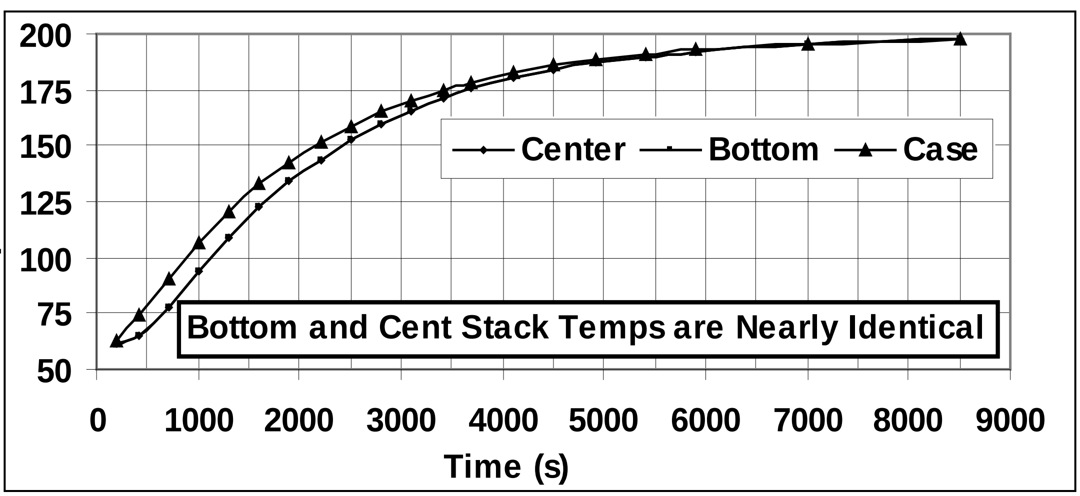

Figure 10. A temperature-time curve used to measure copper–heat pellet stack thermal insulation package thermal conductivity values by alternate transient methods.

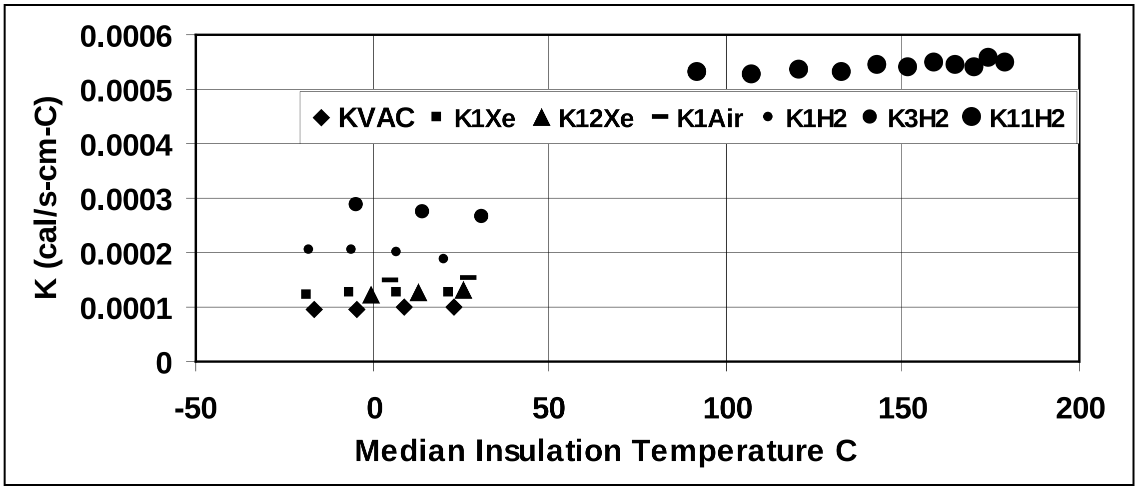

Figure 11. Apparent thermal conductivity values from copper–heat pellet stack cooling curves resulting from ambient temperature changes. (Legend numbers refer to nominal gas pressures in atmospheres).

Apparent thermal conductivity values were measured from ~10 min until ~60 min from the beginning of the experiments. The measured apparent thermal conductivity values were most consistent while the temperature differences between the copper–heat pellet stack and the case remained large. Thermal conductivity values calculated at those approximate times are shown for various gas samples in figure 11. Most of the thermal conductivity data shown in figure 11 was obtained by moving the copper–heat pellet stack RTF fixture between temperature chambers set at –40 ºC and +60 ºC so that the thermal conductivity values measured are clustered near median insulation package temperatures of 0 ºC. Thermal conductivity values at the beginnings and at the ends of these ranges showed irregularities from experimental error and are not shown in figure 11.

The data for the ~11 atm H_2 heating curve in the upper right of figure 11 was obtained by moving the RTF between temperature chambers set at 60 ºC and at 200 ºC. The gas seal and the electrical insulation were damaged after the RTF was heated to 200 °C so that additional data could not be easily obtained using this method. The high temperature, high pressure H_2 gas atmosphere data in figure 11 clearly shows the effect of H_2 gas at high pressure on the thermal insulation package, even when substantial amounts of efficient micro-porous thermal insulators are used. The relevance of the high pressure data is shown by the fact that the GPS9Q battery operated at a similar internal gas pressure (see table 2 and section 6). The low thermal conductivity of the thermal insulation package in Xe at ~11 atm of pressure is encouraging because evolved battery gasses can be mixed with Xe at high pressure to form gas mixtures that will contain significant volumetric percentages of low thermal conductivity Xe gas.

9. LCCM Thermal Cell Heat Generation

Heat generation rates from the thermal cells were determined from calculations that used the measured thermal conductivity values of the thermal insulation packages and the known heat capacities of the cooling components. Estimated heat loss rates along the electrical leads are shown in appendix H, and I^2R electrical heating from the battery stack and leads are estimated in appendix I. Heat generation rates of the thermal cells appeared to increase significantly with the operating stack forces, as can be observed from the measured thermal lifetimes shown in table 2. This effect was not expected to be so significant and is presently attributed to the sustained spring force the silicone rubber disks can apply over a longer distance, when compared with the sustained spring force of the compressed thermal insulation as the molten salt electrolyte melts and the stack height decreases. Overheating of the thermal insulation at the positive end of the cell stack could be a significant contributing factor. Increasing the number of silicone rubber gaskets was correlated with shorter postmortem measurements of thermal cell stack heights, thinner postmortem axial thermal insulation, and increased thermal cell heat generation rates and battery thermal lifetimes. The thermal lifetimes in table 2 show that the LCCM thermal lifetimes could be increased to ~300 s or more from control of thermal cell heat generation when the operating gas atmosphere is a fore pump vacuum. The data in table 2 (GPS9L and GPS9M) shows that the heat generation rates of the thermal cells also increased when the anode thicknesses were decreased.

The total amount of heat generated during battery operation for the GPS9P enhanced 307 A–s capacity thermal cell stack thermal battery that operated at 7 Pa was 294.0 cal, and the heat lost by the cooling components of that battery during battery operation was 236.2 cal. During the operating period at an ambient temperature of –40 ºC, the GPS9P thermal cell stack lost heat at a nominal rate of 3.01 cal/s (*1*). Batteries GPS9N and GPS9P both used the enhanced 307 A–s thermal cell stack with similar thermal insulation packages, and should have had heat loss rates within ~15% of one another under equivalent atmospheric conditions if no heat were generated from the thermal cells. The data in table 2 shows thermal lifetimes to 430 ºC of 106.2 s for GPS9N and 297.8 s for GPS9P. GPS9N and GPS9P were built as identically as possible, and both were tested in a fore pump vacuum in the heavy metal heat sink of the RTF at –40 ºC. Between approximately 200 ºC and 100 ºC, after exothermic reactions should have been complete, the cooling rate for GPS9N was 0.2163 ºC/s and the cooling rate for GPS9P was 0.1821 ºC/s. These cooling rates differ by approximately 20%, which confirms that most of the difference in the observed cooling times to 430 ºC was caused by heat generation from the thermal cell stack.

Significant amounts of heat generation from normally operating lithium/aluminum alloy/iron pyrites (Li/Al alloy/FeS_2) thermal cells have been observed and reported previously. The Manlos flight test thermal battery used a 3 in. diameter thermal cell with a 2758 kPa (400 lb force) spring

to insure thermal cell stack compression during operation. The flight test Manlos thermal cell stack delivered 120 s of required electrical lifetime at currents ranging from 40 to 85 A. The Manlos cell stack temperature rose steadily above 540 ºC, calculated from the thermal cell pyrotechnic heat balance after the electrical lifetime had been delivered, to approximately 620 ºC by ~300 s after battery initiation, and the thermal cells generated 44,400 calories of exothermic heat before the stack cooled back to 540 ºC by ~2000 s after battery initiation (*9*). The previously developed 159 A–s capacity LCCM thermal battery generated 399 cal and lost heat at a nominal rate of 8.36 cal/s at an ambient temperature of –42 ºC during an initial operating period of 80 s at gas pressures ranging from 874 to 549 kPa (*3*).

Thin thermal cells or properly processed heat generator pellets made from altered anode and cathode powders might serve as auxiliary thermal cell stack heat generators. Although the experiments clearly show that large amounts of heat are available from the operating thermal cells, the heat generation rates and amounts must be repeatable if they are to be used in the design of production thermal batteries.

10. Laboratory Flight Test LCCM Batteries

The performance and construction of laboratory flight test batteries GPS9S and GPS9T is described in table 2 and in appendix C. Both of those batteries were tested using electrical ignition at ARL.

GPS9S was tested in the RTF heavy metal heat sink and the RTF temperature did not rise significantly above –40 ºC during the test. External case temperatures measured for GPS9T are shown in figure 12 and are fairly typical, if slightly high, case temperatures for thermal batteries operating with light flight cases in the absence of external heat sinks. The maximum measured case temperature of GPS9T at the case bottom was 267.8 ºC at 25.662 s. The bottom and side case temperatures measured for GPS9T are high because of the heat paper near the case, but case temperatures of 200 ºC to 300 ºC occur frequently during the operation of production thermal batteries. Such elevated case temperatures can contribute to significantly longer lifetimes if metallic heat sinks are absent.

The measured electrical lifetime of GPS9S in the RTF at –40 ºC was 112.9 s, which demonstrated ~25% improvement over the benchmark LCCM thermal battery in the RTF at –40 ºC ambient temperature. GPS9T showed an electrical life of 168.5 s to 11 V at a current drain of 1.5 A when tested at room temperature (~ +21 ºC) in a flight case with no metal heat sinks in contact with the case and with no inertial igniter housing. A flight test battery built as identically as possible to GPS9T was supplied to Picatinny/ARDEC and tested using telemetry in the Picatinny/ARDEC air gun with a 10 ohm load after being potted in epoxy. That battery showed an electrical lifetime to 11 V of 169.3 s when tested at room temperature, as measured using a

caliper from a graphical printout. Room temperature lifetimes of the best LCCM thermal batteries before this ATO were not well characterized, but could be expected to be 130 ±10 s to 11 V at 1.5 A in a heavy metal heat sink.

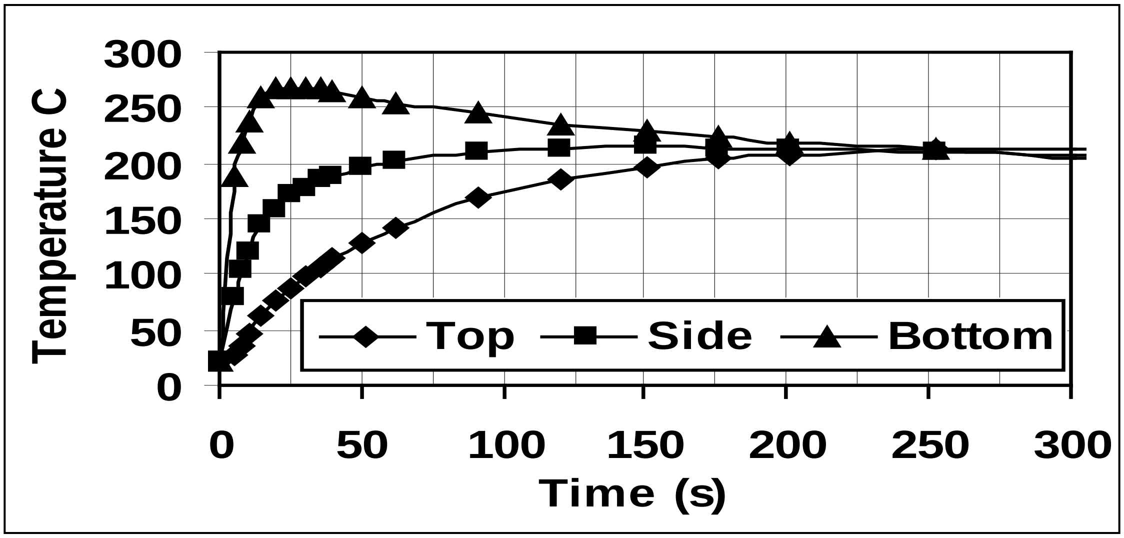

Figure 12. GPS9T flight case operating temperatures.

11. Field Flight Test LCCM Batteries

A total of six field flight test batteries in laser-welded flight cases was sent to Picatinny/ARDEC (figure 1). Field test batteries in flight cases used battery headers laser welded to 304 SS cans. Inertial igniter housings were laser-welded and/or silver-brazed to the SS cans externally and hermetically sealed using E–20NS high temperature epoxy. The hermetic seals were confirmed to better than 10^{-5} std-atm-cc He/s using the helium leak tester. The total mass of a hermetically sealed field flight test battery was approximately 77 g without, and approximately 96 g with, an inertial igniter and its external housing attached to the flight case. All of the inertial igniters functioned properly in flight and air gun tests. Significantly smaller inertial igniters than those used in the flight tests are now available.

Two of the flight test batteries were activated at room temperature using an inertial igniter with an air gun at ARDEC, and both performed successfully. Four flight test batteries were tested at 70 ºF in the 155 mm howitzer at Yuma, AZ on 5 August 2008 after activation by inertial igniters. Those batteries were fired from the 155 mm howitzer using a 95 lb projectile with an M232 zone 5 charge and a nominal spin rate of 244 RPS as the projectiles exited the muzzle. The total flight time was approximately 65 s. Two of those tests were completely successful. One battery might have failed because of initiation difficulties, overheating, or instrumentation difficulties, and one battery was a no-test due to apparent instrumentation difficulties.

Volume reduction and lifetime extension of munitions batteries are both important. An input file, Fortran source program, and output file that can be used to calculate reduced sizes of the LCCM field test batteries with the previously optimized (GPS9N) thermal cell stack to obtain a given lifetime is shown in appendix J.

12. Future Work —LCCM and Copper–Heat Pellet Stack Cooling Curve Comparisons

Data taken from the LCCM batteries and the copper–heat pellet stack cooling curves during the ATO study permit detailed analyses of the operating battery thermal behaviors. Some illustrative examples are shown in figures 13–15. Batteries GPS9N and GPS9P in table 2 were built as identically as possible and tested under identical conditions. Analysis of the cooling curves shown in figure 13 clearly shows that GPS9P generated significantly more heat than GPS9N. The electrical performance of GPS9P was not greatly reduced as a result of the heat generation because GPS9P delivered 176.9 s to 11 V at 1.5 A compared with 142.7 s for GPS9N. Postmortem analysis of GPS9P showed that the cell stack decreased ~0.040 in. in height during discharge (0.795 in. to 0.755 in.). GPS9N did not show a measurable decrease in stack height during discharge (0.770 in. measured during construction and 0.784 in. measured after discharge). The data taken during battery construction and the data from the cooling curves suggest that the insulation heating at the positive end of GPS9P was greater than that of GPS9N. The resulting higher initial temperatures at the GPS9P thermal cell stack positive end could have contributed to the sustained heat generation and improved GPS9P electrical performance.

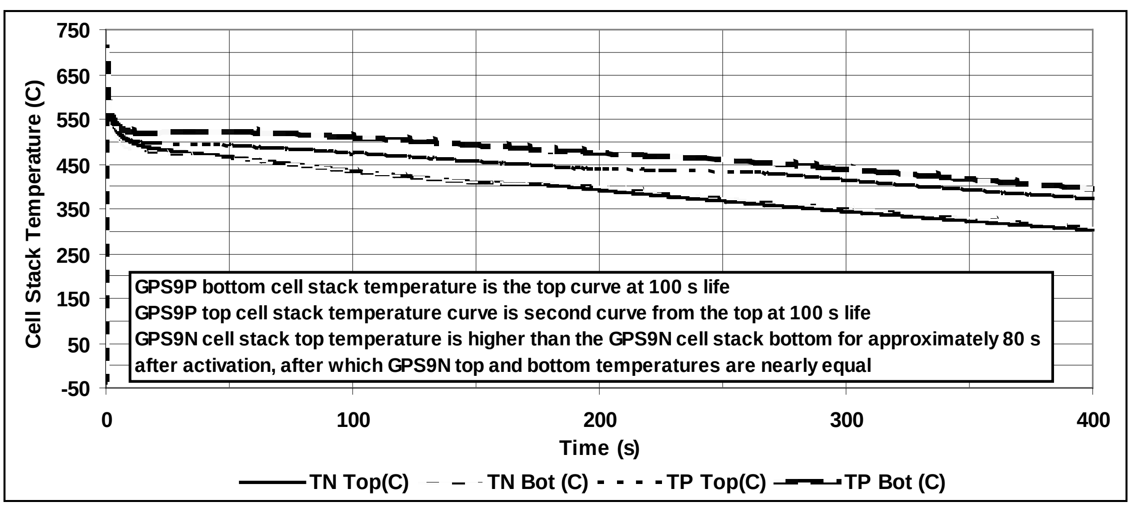

Figure 13. Cooling curves for GPS9N and GPS9P.

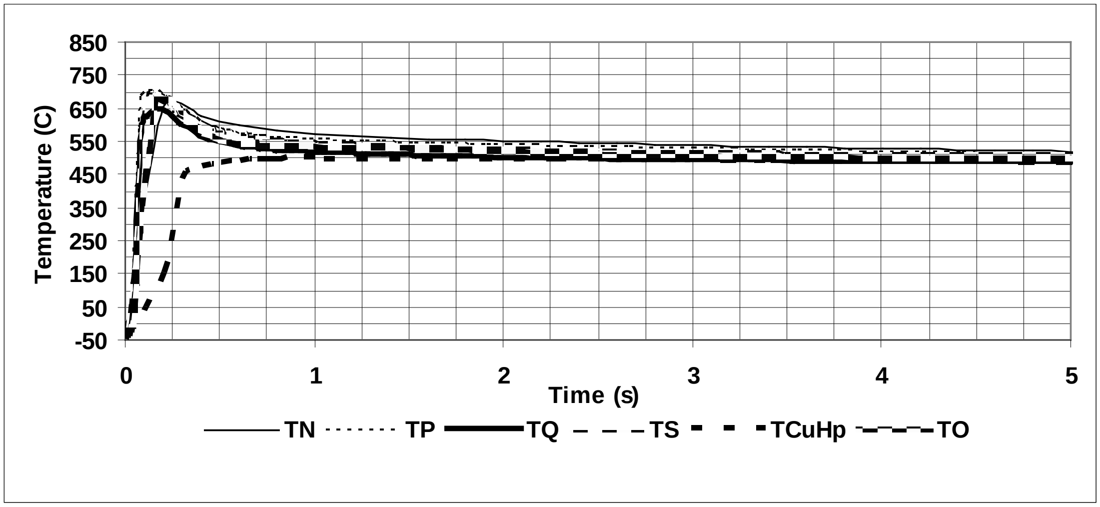

Figure 14. LCCM and copper–heat pellet stack top cooling curves.

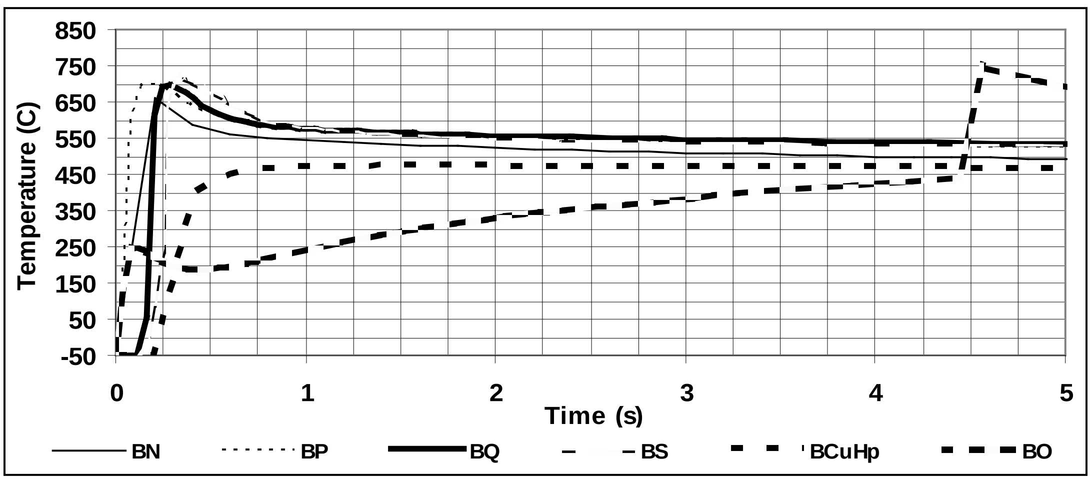

Figure 15. LCCM and copper–heat pellet stack bottom cooling curves.

The first 5 s of the temperature time curves for the thermal batteries using the enhanced 307 A–s thermal cell stack and for the copper–heat pellet stack are shown in figures 14 and 15. Figure 14 shows the stack top temperature traces, and figure 15 shows the stack bottom temperature traces. The data shows the experimental temperature spread for thermal batteries that were all built with cell stacks as identical as possible. The cooling curves of figures 14 and 15 show more variation from one another at the stack bottom, where heat paper amounts were less closely controlled because of the construction methods used and the need to insure battery initiation.

The temperatures measured for the copper–heat pellet stack are noticeably lower than those of the thermal batteries, even though the heat capacity of copper is well-known and the heat outputs of the heat pellets have been well-characterized. When initiated at –40 ºC, the calculated maximum temperature of an individual thermal cell is 555.8 ºC (appendix D–4), and that of an individual copper–heat pellet stack simulated thermal cell consisting of one heat pellet and four

copper disks is 574.6 ºC (appendix F–3). The low experimental temperatures for the copper–heat pellet stack are partly caused by the fact that the heat pellets in the copper–heat pellet stack were all placed with two copper disks on each side (12 heat pellets and 48 copper disks). The thermocouples for the thermal batteries, by contrast, were all spot-welded to 0.003 in. thick SS disks that were placed directly against the heat pellets at the cell stack ends. The thermal cell stack ends were inherently overheated because 10 heat pellets were used with nine thermal cells. The thermal conductivities of the thermal cell components are less than that of the copper, which permits more localized heating at the thermocouple junctions. Finally, heat transfer from the high thermal conductivity copper disks into the thermal insulation could be expected to be more rapid than that from the low thermal conductivity thermal cells during the transient heat transfer state immediately after heat pellet initiation.

The data in figures 14 and 15 suggest that GPS9O in table 2 failed because of a late firing heat pellet near the stack bottom. This suggests that the life of the flight test batteries could be increased significantly simply by increasing the stack pressure or by using a spring to maintain a constant stack force during battery operation. More heat in the bottom end thermal insulation might be helpful (figure 13). Control of heat generation by the use of increased stack force and/or the use of specialized heat generating thermal cells, combined with the anticipated successful use of gas gettering materials in the near future, appear to offer significant improvements for heat limited thermal batteries. The amount of hydrogen gas evolved can also be reduced by using improved materials selection and chemical processing methods.

13. Summary and Conclusions

Construction and operating characteristics of LCCM thermal batteries have been documented and discussed. Volumetric energy densities of the LCCM thermal battery were increased by ~25% over those of a benchmark battery primarily by improved battery construction and by heating of the side wall thermal insulation (*1*). Experimental results and calculations indicate that the removal of ~50 std–atm-cc (~4.5 mg) of H_2 gas by gas gettering or by improved chemical processing methods could increase the LCCM thermal lifetime to three times the original LCCM benchmark battery value (~90 s to ~300 s). Because the present cell stack can deliver only 307 useful A–s, the lifetime of a battery using that cell stack and using a current of 1.5 A would be limited to 307/1.5 = ~205 s, and a ~300 s lifetime LCCM thermal battery using that thermal cell stack would operate at a current drain of ~1 A. With an increased thermal cell diameter, the LCCM volumetric energy density could be increased to ~60 Wh/l by improved gas control, battery construction methods, materials selection, and chemical processing methods while using the present external package size (*5*).

GPS9N and GPS9P (table 2 and section 12) were built as identically as possible and discharged under identical conditions. Both batteries performed well electrically but showed differences in

thermal lifetimes of a factor of ~3 because of the heat generation from the thermal cells. Normally occurring exothermic reactions prolonged the GPS9P operating lifetime to 176.9 s and permitted GPS9P to deliver 176.9x1.5/307=0.86 of its calculated electrochemical capacity (appendix D–6). The thermal lifetime of GPS9P measured in a fore pump vacuum (~7 Pa) was 297.8/90.9 = 3.28 times that of the best benchmark thermal battery GPS9H (table 2).

Battery construction methods based on experience obtained during construction and analysis of the GPS9R battery in table 2 are anticipated to produce successful gas getter operation in the near future. A search for novel thermal insulators showed that the control of gas atmospheres in existing micro-porous or multifoil thermal insulators is presently the most effective method of reducing heat losses.

Control of temperature through heat generation during normal thermal cell operation appears very promising from examination of the data in table 2. The 3 in. diameter thermal cell Manlos thermal battery with the 400 lb force internal spring used to maintain force on the thermal cell stack generated 44,400 cal from chemical exothermic reactions, which helped to hold the thermal cells above 540 °C for 2000 s (*9*).

More efficient thermal insulation heating methods using nanofoil heat sources rather than heat paper might help to reduce the case temperatures (*10*). Heating of the thermal insulation by nanofoils could also help to more effectively heat the thermal insulation near the thermal cell stack and reduce initial rapid heat loss rates from the thermal cell stack during the earliest portions of the transient state. Better control of heat losses and enhanced thermal insulation heating methods are expected to enhance the performance of conformal thermal batteries in which geometric configurations can contribute significantly to difficulties with heat transfer. The experiments and calculations of this study confirmed previous results showing that submunition thermal batteries 6 mm tall by 5 mm diameter could be made to operate for approximately 10 min.

14. References

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Appendix A. Construction Detail – Benchmark 194 A–s LCCM Battery – (GPS9G)

Construction details of the 194 A–s benchmark LCCM battery GPS9G are summarized and explained briefly in the table below. GPS9G used Min-k thermal insulation on the battery sides and ends. No Microtherm was used and the side wall thermal insulation did not use any auxiliary pyrotechnic heating.

GPS9G Construction Detail (14 February 2007 Test)	
Component/Procedure	Mass (g)
Positive collector plus lead total metal mass including type K thermocouple wires - Power ribbons were 304 SS ~3 in. x ~0.110 in. x 0.003 in. and thermocouple wires were 0.010 in. diameter.	0.426
Negative collector plus lead total metal mass including type K thermocouple wires - Power ribbons were 304 SS ~3 in. x ~0.110 in. x 0.003 in. and thermocouple wires were 0.010 in. diameter.	0.401
Weighed RTF with male swage fitting and Teflon tape	1300.5
Weighed RTF lid	232.251
Weighed six 6-32 SS Holo-Krome Allen cap screws	9.313
Match total metal mass (0.332 in. long, 0.003 in. diameter Nichrome bridge wire with ~3.89 and 4.32 in. long nickel leads each ~0.050 in. wide x 0.003 in. thick) - The Fluke meter showed 2.5 ohm resistance at the triply folded nickel ribbons and 2.8 ohm resistance at the nickel ribbon ends.	0.173
Fourteen 0.75 in. diameter blank 304 SS cell covers (0.0431 in. thick total)	2.407
Eighteen 0.75 in. diameter blank heat pellets (0.3892 in. thick total)	10.776
Nine 0.75 in. diameter blank anode pellets, Li/Al powder (90 mass % 20/80 Li/Al alloy, 10 mass % LiBr–LiCl–LiF eutectic electrolyte) never dried or heated above room temperature (0.2141 in. thick total)	2.251
Nine 0.75 in. diameter blank E/C pellets dried in vacuum at 110 ºC. Dry room went down during this drying period. Closed all valves to vacuum oven to protect E/C pellets. The total thickness of the nine E/C pellets was 0.2105 in. and the E/C pellets lost 0.287% of their original mass while drying.	4.610
The E/C pellet chemical composition of the optimization program for the baseline LCCM thermal batteries was calculated from 2228 Sep 30 2006 13:27 baseec.for. The E/C of baseec.for used a 45/55 sep/cat weight ratio and a 53/47 E/B weight ratio. The actual E/C construction target weights were 0.2308 g separator, 0.2821 g cathode, 0.5129 g total. The actual E/B ratio used in the GPS9F cathode was 55/45 because that powder was already processed and available.	
Positive lead electrical insulation 1.524 – 0.426 = 1.098	1.098
Negative lead electrical insulation 0.848 – 0.401 = 0.447	0.447
Begin mandrel assembly here on the bottom 0.75 in. diameter steel rod. Components are added in the order shown below.	
0.75 in. Diameter blank mica disk 0.0041 in. thick with 2 parallel #69 Scotch tape strips each ~2.25 in. long x ~0.0625 in. wide x 0.006 in. thick	0.161
~ 0.755 in. Diameter Min-k disk ~0.054 in. – ~0.058 in. thick with ~0.25 in. x ~0.25 in. through notch	0.096

ARL heat paper (2 strips, NBS 390 cal/g powder) one ~0.25 in. x ~0.40 in. and one ~0.25 in. x ~0.25 in. strip, both strips ~0.026 – .028 in. individual thickness, total mass 0.109 g. (This heat paper was placed in notch of the 0.096g Min-k disk above). Placed the ~0.25 in. x ~0.25 in. strip in the notch and then placed the ~0.25 in. x ~0.40 in. strip in the notch.	0.109
0.75 in. diameter mica disk ~0.0045 in. thick with ~0.25 in. x ~0.25 in. through notch. Placed on Min-k notched disk so the notches lined up.	0.069
Four heat pellets of total mass 2.403 g and total thickness 0.0796 in. thick. Placed the heat pellets directly on to the notched mica and the ARL heat paper.	2.403
~0.75 in. diameter blank mica disk ~0.0032 in. thick	0.065
~0.75 in. diameter blank Min-k disk ~0.142 in. thick	0.291
Negative current collector plus lead described above	0.848
Begin cell stack assembly (nine thermal cells: ten heat pellets, 14 SS disks, nine anodes, nine electrolyte-cathode double layer pellets) here with negative lead and complete cell stack assembly here with positive lead. There are 3 SS disks between the cell stack and each of the stack end heat pellets. The positive and negative current collectors, with their spot-welded type K thermocouples and SS lead ribbons attached, are on the outer ends of the cell stack after the end heat pellets with the lead wires welded to the sides facing the thermal insulation. After the cell stack assembly is complete, continue with 0.75 in. diameter thermal insulation and heat pellets to complete the mandrel assembly.	
Positive current collector plus lead described above	1.524
Positive and negative leads are about 180º apart. Fuse strip is about 45º from negative lead.	
~0.75 in. diameter blank Min-k Disk ~0.144 in. thick	0.316
~0.75 in. diameter blank mica disk ~0.0039 in. thick	0.075
Four heat pellets of total mass 2.388 g and total thickness 0.0799 in.	2.388
~0.75 in. diameter mica disk ~0.0042 in. thick with ~0.25 in. x ~0.25 in. notch cut from diameter	0.068
~0.720 – 0.735 in. diameter Min-k disk ~0.056 – 0.058 in. thick with ~0.25 in. x ~0.25 in. through notch – Placed the 0.100 g Min-k disk on the 0.068 g mica disk so the notches lined up.	0.100
One heat paper strip ~0.25 in. x ~0.25 in. and one heat paper strip ~0.40 in. x ~0.25 in. of individual thicknesses ~0.025 in – .0.027 in. – total mass 0.088 g of 390 cal/g powder heat paper placed into Min-k notch with the ~0.25 in. x ~0.25 in. strip directly against the 4 heat pellets	0.088
~0.75 in. diameter blank mica disk 0.0050 in. thick	0.095
~0.747 – 0.749 in. diameter blank mica disk 0.0044–0.0046 in. thick with two parallel #69 Scotch tape strips ~2.25 in. long x ~0.0625 in. wide x 0.006 in. thick. The four #69 end tape strips overlap the mica disk diameters by about equal amounts. Lined the four end tape strips on the top end of the mandrel assembly with the four #69 end tape strips on the bottom of the mandrel assembly.	0.174
Mandrel assembly is now complete.	
Compressed cell stack under 170 pounds force with an 0.75 in. diameter steel rod at dew point –65.4 °C and removed chips with Accuwipes, forceps, scriber magnet, plug in light, and vacuum cleaner. Many pellet chips. Min-k seemed nonuniform under positive lead. Problem with stack tilting. Released and reapplied 170 pounds force several times.	
Thermal cell stack fuse strip (388 cal/g heat paper) ~1.23 in. x ~0.36 in. – 0.37 in. x ~0.020 – 0.023 in.	0.147
Discard excess NBS 390 c/g heat powder paper	0.007
Mica-tape fuse strip backing (mica is ~1.31 in. x ~0.345 in. x ~0.0038 in. – 0.0041 in. with mass 0.081 g). Used ~2.5 in. x ~0.25 in. x 0.006 in. #69 Scotch electrical tape to hold mica in place by taping to steel rods. The total mica–tape mass is 0.177 g.	0.177
Fiberfrax strip 970 F ~2.675 in. – ~2.680 in. x ~1.170 in. – 1.183 in. x ~0.022 in. (thickness measured by hand held micrometer)	0.510

Used the eight #69 Scotch tape end strips on the mica disks at the two mandrel ends to tape the Fiberfrax wrap in place.	
Cut two mica strips, each strip ~0.28 in. x ~0.70 in. x ~0.004 in. of total mass 0.080 g. Placed one end of the mica strips at the positive end cell cover-lead junction and taped the other end of the mica strips to the top steel rod. This mica will help to protect the positive lead when the four heat pellets in the positive end thermal insulation are initiated.	0.080
~20.0 in. of non-adhesive glass tape 1.223 g, add #69 Scotch electrical tape, one piece ~2 .8 in. x ~0.25 in. x ~0.006 in. to each end of the non-adhesive tape – total mass of the 3 tapes 1.405 g	1.405
Cell stack height ~0.671 in. @ 170 lb force	
Steel rod to steel rod distance 1.150 in. @ 170 lb force	
RTF inner length 1.237 in. to 1.2395 in.	
RTF inner diameter 1.243 in. to 1.248 in.	
RTF outer length 2.068 in.	
RTF outer diameter 2.670 in.	
Lid thickness 0.325 in.	
Lid diameter 2.670 in.	
Taped mica (~1.34 in. x ~0.35 in. x ~0.0041 in.) under positive lead along cell stack side with #69 Scotch tape	0.086
Taped the 0.086 g mica strip under the positive lead. Forced the positive lead into the cell stack side with hardened steel piece.	
Removed excess #69 tape and mica attached to steel rods	0.151
Increased the stack force to 180 pounds with an 0.75 in. diameter steel rod and wrapped the entire battery stack twice with 1.250 g of 0.5 in. wide #69 Scotch electrical tape.	1.250
Measured the cell stack diameters at 0.845 – 0.890 in. after pushing positive lead against cell stack side with a hardened steel piece.	
Removed the assembly from the steel rods and weighed the assembly at 27.359 g at –66.5 ºC dew point. Measured the uncompressed height at 1.212 in. with the vernier calipers.	27.359
Shaved a blank Min-k disk 0.75 in. diameter to 0.055 in.–0.062 in. and 0.118 g mass. Cut one of the negative end #69 tape strips, placed the 0.118 g Min-k disk under that tape strip and applied 180 pounds force to reinforce the tape junction.	0.118
Removed assembly from press, removed excess mica from positive end, and reweighed the assembly at 27.492 g.	27.492
Placed two blank mica disk bottom liners ~1.875 in. diameter x ~0.0073 in. total thickness and 0.363 g total mass into the bottom of the RTF	0.363
Min-k blanket pressed over ~3.43 in. of its length at a time at ~7000 lb and then trimmed. After pressing and trimming the Min-K blanket weighed 6.721 g and measured ~3.55 in. x ~1.24 in. x ~0.132 in. – 0.142 in.. Placed the Min-k blanket into the RTF ID and forced it against the RTF ID with a 0.75 in. diameter steel rod. The Min-k blanket ends then met neatly and the top of the Min-k blanket was about even with the top of the RTF.	6.721
Mica inner liner ~3.31 in. x ~1.412 in. x ~0.0041 in. Placed the mica inner liner into the Min-k blanket ID and forced it against the Min-k blanket with a 0.75 in. diameter steel rod.	0.798
Cut out the ~0.25 in. x ~0.25 in. notch in the negative end mica disk that covered the NBS heat paper that will form the connection to ignite the thermal cell stack fuse strip paper.	0.016
Removed 0.015 g of the mica-tape fuse strip backing.	0.015
Used ~0.005 g Kapton tape to tape nickel match leads into place so that the nichrome wire was directly over the NBS heat paper in the ~0.25 in. x ~0.25 in. notch in the negative end mica tape assembly.	~0.005

Put a small rolled cylinder (~ .038 g) of Kapton tape on top of the notched mica disk with the match taped to it.	~0.038
Blank mica disk ~ .75 in. diameter by ~ .0041 in. thick	0.075
Shaved blank Min-k disk ~.75 in. diameter to ~.071 – 0.077 in. thickness and 0.169 g. Applied 170 lb force to bring the top of the 0.169 g Min-k disk to within 0.004 in. of the top of the reusable test fixture.	0.169
Held stack force at ~170 pounds with a 0.75 in. diameter steel rod and added 0.078 g of 0.5 in. wide Kapton tape to the power and match leads.	0.078
Used the same gaskets as were used for GPS9F. To obtain a hermetic seal between the RTF case and lid, first tried one silicone rubber disk 2 1/8 OD x 1/32 in. thick with six 3/16 in. diameter holes on a 1 in. diameter circle for electrical leads. Then added a Viton disk 2 1/8 in. diameter x 0.25 in. thick with six 3/16 in. diameter holes on a 1 in. diameter circle for electrical leads and added a second silicone rubber disk 2 1/8 OD x 1/32 in. thick with six 3/16 in. diameter holes on a 1 in. diameter circle for electrical leads. Led all electrical connections through over the top of the second silicone rubber disk and then added four additional silicone rubber gaskets (two silicone rubber gaskets 2 1/8 in. OD x 1 in. ID followed by two silicone rubber gaskets 2 1/4 in. OD x 1 in. ID. Each silicone rubber gasket was ~1/32 in. thick and the bottom of the RTF lid was 0.21 – 0.25 in. from the RTF top after sealing with 6-32 Holo-Krome Allen cap SS screws. Used no vacuum grease at all with any of the rubber gaskets.	
Removed the RTF lid and measured the top of the 0.169 g shaved Min-k disk at ~0.025 in. below the RTF top under 170 lb stack force and at ~0.050 in. above the RTF top under 0 lb stack force.	
Used the 2 1/16 in. diameter Diacro die to cut the OD of the Viton disk to 2 1/16 in. Used the 1 1/4 in. diameter Diacro die to cut 1 ¼ in. center holes out of all of the silicone rubber disks. Then replaced the modified gaskets starting at the RTF top as follows. First used one silicone rubber disk 2 1/8 in. OD x 1 ¼ in. ID x 1/32 in. thick. Then added the Viton disk 2 1/16 in. diameter x 0.25 in. thick with six 3/16 in. diameter holes on a 1 in. diameter circle for electrical leads and added a second silicone rubber disk 2 1/8 in. OD x 1 ¼ in. ID x 1/32 in. thick. Led all electrical connections through over the top of the second silicone rubber disk and then added four more silicone rubber gaskets (two silicone rubber gaskets 2 1/8 in. OD x 1 1/4 in. ID followed by two silicone rubber gaskets 2 1/4 in. OD x 1 1/4 in. ID). Each silicone rubber gasket was ~1/32 in. thick and the bottom of the RTF lid was 0.20 – 0.23 in. from the RTF top after sealing with 6-32 Holo-Krom Allen cap SS screws. Used no vacuum grease at all with any of the rubber gaskets. Only five of the six 6-32 screw holes were good. Made the hermetic seal with the 5 screw holes and did not use a "C" clamp. Did not record the postmortem stack top depression. All of the above GPS9G gaskets had been previously used in GPS9F.	

Appendix B. Construction Detail Enhanced 307 A–s LCCM Battery (GPS9Q)

Some construction details and procedures for the GPS9Q thermal battery, which used the enhanced 307 A–s thermal cell stack, are summarized and explained below. GPS9Q was sealed in one atmosphere of dry room air at dew point –57.1 ºC and then initiated at an ambient temperature of –40 ºC. GPS9Q showed an electrical lifetime of 99.4 s to 11 V at 1.5 A and a thermal lifetime of 154.3 s to 430 ºC with a nominal operating gas pressure of 10.7 atm (table 2, main report).

GPS9P was built as identically as possible to GPS9Q, and was discharged with a fore pump vacuum as the operating gas atmosphere after collecting a gas sample during the first 10 s of operation. GPS9P delivered 176.9 s to 11 V at 1.5 A with a thermal life of 297.8 s to 430 ºC when initiated at an ambient temperature of –40 ºC (table 2, main report). Note that the maximum electrical lifetime of the 307 A–s thermal cell stack when operating at a current of 1.5 A is nominally 307/1.5 = 205 s. The GPS9Q cell stack cooled 2.87 times faster than the GPS9P cell stack between the temperatures of 200 ºC and 100 ºC.

GPS9Q Construction Detail (10 December 2007 Test)	
Component/Procedure	Mass (g)
Positive lead total metal mass including type K thermocouple wires 0.556 g Total positive lead mass including #69 Scotch tape and mica insulation 0.967 g (SS ribbon was ~5.10 in. x ~0.110 in. wide by 0.003 in. thick)	0.556
Negative lead total metal mass including type K thermocouple wires 0.521 g Total negative lead mass including #69 Scotch tape and mica insulation was 0.835 g (SS ribbon was ~5.10 in. x ~0.110 in. wide by 0.003 in. thick)	0.521
Match total metal mass (0.293 in. long, 0.003 in. diameter Nichrome bridge wire with ~5.1 in. long nickel leads each 0.050 in. wide x 0.003 in. thick) – (~2.3 ohm resistance at the nichrome wire ends and ~2.8 ohm resistance at the nickel ribbon ends)	0.226
Fourteen 0.75 in. diameter blank 304 SS cell covers (0.0433 in. thick total)	2.423
Ten 0.75 in. diameter blank heat pellets	7.415
Nine 0.75 in. diameter blank anode pellets (Li/Al powder 90 mass % /eutectic LiBr–LiCl–LiF electrolyte 10 mass %) - never dried or heated above room temperature	2.368
Nine 0.75 in. diameter blank E/C pellets – The powders used to make these nine E/C pellets were originally dried at 197 ºF for 23 h and 29 min in a vacuum desiccator with a liquid nitrogen trap in place on 22 June 2006.	5.958
The E/C pellet chemical composition of the optimization program was calculated from 2228 June 8 2007 13:10 ec47L.for. The E/C of ec47L.for used a 34/66 sep/cat weight ratio and a 53/47 E/B weight ratio. The actual E/C construction target weights for GPS9Q were 0.222 g separator, 0.445 g cathode, and 0.667 g E/C. The actual E/B ratio used in the GPS9Q cathode was 55/45 because that powder was already processed and available.	
Positive lead electrical insulation 0.967-0.556	0.411
Negative lead electrical insulation 0.835-0.521	0.314

Begin mandrel assembly here on the bottom 0.75 in. diameter steel rod at dew point –67.5 ºC.	
0.75 in. diameter blank mica disk 0.0049 in. thick with 2 parallel #69 Scotch tape strips each ~2.25 in. long x ~.08 in. wide x 0.006 in. thick – negative stack end mica-tape	0.140
0.75 in. diameter Microtherm disk 0.0858 in. thick with 0.25 in. x 0.25 in. through notch	0.182
ARL heat paper (3 strips, NBS 390 cal/g powder) one 0.25 in. x 0.4 in. and two 0.25 in. x 0.25 in. strips all ~0.029 in. individual thickness, total mass 0.175g (This heat paper was placed in the notch of the 0.182 g Microtherm disk above) - Placed the two ~0.25 in. x ~0.25 in. pieces into the notch and then placed the ~0.4 in. x ~0.25 in. piece into the notch.	0.175
0.75 in. diameter blank mica disk 0.0045 in. thick	0.089
0.75 in. diameter blank Microtherm disk 0.0878 in. thick	0.206
Negative current collector plus lead and insulation described above	0.835
Begin cell stack assembly here. Use nine thermal cells, ten heat pellets, 14 SS disks, nine anodes, and nine electrolyte-cathode double layer pellets. The cell stack assembly is then completed with the positive lead. There are three SS disks between the cell stack and each of the stack end heat pellets. The positive and negative current collectors with their spot-welded type K thermocouples and SS lead ribbons attached are on the outer ends of the cell stack after the end heat pellets with the lead wires welded to the sides facing the thermal insulation. After the cell stack assembly is complete, add the 0.75 in. diameter thermal insulation and heat paper to complete the mandrel assembly.	
Positive current collector plus lead described above	0.967
0.75 in. diameter blank Microtherm disk 0.0874 in. thick	0.231
0.75 in. diameter blank Microtherm disk 0.0873 in. thick	0.228
0.75 in. diameter blank SS disk 0.0032 in. thick	0.172
0.75 in. diameter blank heat paper disk 375 cal/g 0.0225 in. thick	0.192
0.75 in. diameter mica disk ~ 0.0046 in. thick with ~0.25 in. x ~0.25 in. through notch	0.080
0.75 in. diameter Microtherm disk ~0.0869 in. thick with ~0.25 in. x ~0.25 in. through notch	0.191
Two heat paper strips ~0.25 in. x ~0.25 in. and one heat paper strip ~0.40 in. x ~0.25 in. of individual thicknesses; ~0.0250 in. – 0.0253 in. with total mass 0.142 g of NBS 390 cal/g heat powder paper placed into Microtherm notch with the ~0.4 in. x ~0.25 in. strip directly against the 0.192 g heat paper disk	0.142
~0.75 in. diameter blank mica disk 0.0039 in. thick with two parallel #69 Scotch tape strips each ~2.25 in. long x ~0.09 in. wide x 0.006 in. thick – Aligned the four #69 end tape strips on the top end of the mandrel assembly with the four #69 end tape strips on the bottom of the mandrel assembly.	0.137
Mandrel assembly is now complete.	
Compressed cell stack under 180 lb force with an 0.75 in. diameter steel rod at a dew point of –63.3 °C and removed the many pellet chips formed with Accuwipes, forceps, scriber magnet, plug in light, and vacuum cleaner. About 60% of the chips were magnetic (heat pellet chips) and about 60% of the nonmagnetic chips reacted with water (anode chips).	
Thermal cell stack fuse strip (388 cal/g heat paper ~1.18 in. x ~0.255 in. x ~0.0158 in.)	0.091
Discard excess NBS heat paper made from 390 c/g heat powder	0.008
Mica-tape fuse strip backing (mica is ~1.339 in. x ~0.208 in. – ~0.212 in. x 0.0046 in. ~0.0047 in. and 0.058 g) Use ~3.0 in. x ~0.19 in. x 0.006 in. #69 Scotch electrical tape to hold mica in place by taping mica to steel rods – total mica-tape mass is 0.140 g	0.140
Fiberfrax strip 970 F ~2.640 in. – 2.648 in. x ~1.128 in. – 1.158 in. x ~0.0201 in. – 0.0203 in. (thickness measured by hand held micrometer)	0.484
Cut an internal slit for the positive lead and an external slit for the negative lead and taped the Fiberfrax strip around the cell diameter with the smooth Fiberfrax surface facing the cells using the eight #69 Scotch tape end strips on the mica disks at the two mandrel ends.	
~10.0 in. of non-adhesive glass tape 0.588 g, add #69 Scotch electrical tape, one piece ~2.8 in. x ~0.25 in. x 0.006 in. to each end of non-adhesive tape (total mass of the 3	0.804

tapes 0.804 g)	
Cell stack height 0.760 in. – 0.770 in. @ 190 lb force	
Steel rod to steel rod distance 1.155 in. – 1.165 in. @ 190 lb force	
RTF inner length 1.237 in. to 1.2395 in.	
RTF inner diameter 1.243 in. to 1.248 in.	
Mica under positive lead (~1.24 in. x ~0.21 in. x ~0.0048 in. 0.056 g mica) Added two #69 Scotch tape strips each strip ~2.0 in. x ~0.125 in. x 0.006 in. and weighed the mica-tape assembly at 0.133 g	0.133
Taped mica strip under positive lead with #69 Scotch tape and forced positive and negative leads against the cell stack diameter with a hardened steel piece.	
~10.0 in. of non-adhesive glass tape 0.594 g add #69 Scotch electrical tape one piece ~2.8 in. x ~0.25 in. x ~0.006 in. to each end of non-adhesive tape (total mass of the three tapes was 0.806 g) Taped the positive and negative leads into place along the cell stack side with the 0.806 g tape assembly.	0.806
Remove 0.051 g # 69 Scotch electrical tape that had been holding the fuse strip to the steel rods. Measure cell stack diameter at 0.780 in. to 0.920 in. Diameter was greatest at positive lead because positive lead was ~180 degrees from fuse strip. Avoid this in the future.	0.051
~20 in. of non-adhesive glass tape 1.183 g add #69 Scotch electrical tape one piece ~2.8 in. x ~0.25 in. x ~0.006 in. to each end of non-adhesive tape (total mass of the 3 tapes 1.399 g)	1.399
Inner Microtherm wrap ~2.76 in. x ~1.31 in. x ~0.089 in. (gray)	1.840
Single heat paper wrap ~3.43 in. x ~1.32 in. x ~0.0221 in. 375 cal/g paper	1.910
Outer Microtherm wrap ~ 3.46 in. x ~1.34 in. x ~0.088 in. (gray)	2.468
The inner and outer Microtherm wraps, but not the heat paper, were pressed at ~6600 lb over 3.42 in. of their lengths at a time so that the wrapped cell stack would fit into the test fixture. The Microtherm characteristics after pressing are shown below.	
Inner Microtherm wrap ~2.87 in. x ~1.41 in. x ~0.056 in. (gray)	1.816
Outer Microtherm wrap ~3.57 in. x ~1.41 in. x ~0.067 in. (gray)	2.443
Assembled the three side wrap pieces in sequence, increased the stack force to 190 lb with an 0.75 in. diameter steel rod, taped the ~20 in. non-adhesive glass tape to the non-adhesive glass tape already on the cell stack outer diameter with one of the #69 Scotch adhesive end tape strips, and then taped all three side wraps to the cell stack side at once. Held the assembly in place using the adhesive strip on the other end of the non-adhesive strip. Then taped the entire outer diameter one time with #69 Scotch adhesive tape. The insulation wrap outer diameter then ranged from 1.106 in. to 1.245 in. (mostly 1.17 in. to 1.23 in.). Weighed the wrapped cell stack assembly at 31.496 g and then dried in vacuum at room temperature with an electronic cold trap in place.	31.496
Placed two blank mica disk bottom liners ~1.185 in. diameter x ~0.0072 in. total thickness into the bottom of the flight case (0.360 g total mass).	0.360
Placed a 375 cal/g blank heat paper disk ~1.25 in. diameter x ~0.018 in. thick on the two bottom mica liners.	0.414
Cut out the ~0.25 in. x ~0.25 in. notch in the positive end mica disk that covered the NBS fuse strip heat paper.	0.010
Cut away excess side wrap insulation and heat paper to bring the top of the side wall insulation and heat paper even with the top of the flight case while the stack was under 180 lb force. Reweighed the cell stack at 30.438 g.	30.438
Cut out the ~0.25 in. x ~0.25 in. notch in the negative end mica disk that covered the NBS fuse strip heat paper.	0.013

Scrubbed the negative end 0.75 in. diameter mica disk with Accuwipes and forceps and added two #69 Scotch tape strips. Each strip ~2.2 in. x ~0.09 – ~0.100 in. x 0.006 in. was taped directly to one of the #69 tape strips already on the 0.75 in. diameter mica disk. Both ends of the 2.2 in. long Scotch #69 tape strips protruded about equally past the negative end mica disk diameter.	0.063
Used ~0.005 g Kapton tape to tape nickel match leads into place so that the nichrome wire was directly over the NBS heat paper in the ~0.25 in. x ~0.25 in. notch of the negative end mica tape assembly.	~0.005
Placed a 375 cal/g heat paper disk ~0.75 in. diameter x ~0.0195 in. thick directly onto the top of the negative end mica-tape assembly.	0.173
Blank mica disk ~0.75 in. diameter by ~0.0040 in. thick.	0.074
Shaved Microtherm disk ~0.75 in. diameter x ~0.054 – 0.062 in. thick.	0.140
Bent the ~2.25 in. long Scotch #69 tape strips over the top of the shaved 0.140 g Microtherm disk and taped them together adhesive side up removing 0.002 g of the #69 tape in the process.	
0.75 in. diameter blank mica disk 0.0044 in. thick – placed directly on the exposed Scotch #69 tape adhesive.	0.089
Used an 0.75 in. diameter steel rod with 180 lb force to bring the top of the 0.089 g mica disk within 0.004 in. – 0.009 in. of the top of the ~1300 g reusable test fixture.	
With the steel rod maintaining 180 lb on the cell stack top insulated the lead wires and covered the heat paper/insulation side wrap top area with Scotch #69 glass tape. Lifted the GPS9Q cell stack out of the reusable test fixture with no difficulty and weighed the cell stack at 31.413 g.	
Sealed with 6-32 SS Holo-Krome Allen cap screws using five blank silicone rubber gaskets 2 3/16 in. diameter and one silicone rubber gasket 2 3/16 in. OD x 1 ¼ in. ID. Each silicone rubber gasket was ~1/32 in. thick and the bottom of the RTF lid was 0.068 in. – 0.102 in. from the RTF top after sealing. The final mass of GPS9Q after sealing into the RTF was 1589.4 g.	
On postmortem the top of the 0.089 g blank mica disk was 0.025 in. – 0.032 in. below the top of the RTF with no compressive force applied. When 180 lb of compressive force was applied, the top of the 0.089 g blank mica disk was 0.062 in. below the top of the RTF.	

Appendix C. Construction Detail LCCM Flight Test Battery (GPS9T)

The table below briefly summarizes and explains some construction details and procedures for the GPS9T flight test thermal battery that was built into a laser-welded flight case and tested with no external heat sink using electrical initiation at room temperature at ARL. GPS9T used the enhanced 307 A–s thermal cell stack and delivered 168.5 s to 11 V at 1.5 A when initiated at ~21 ºC (table 2, main report). GPS9T did not use an external inertial igniter and did not have an external inertial igniter housing attached to the battery case.

GPS9T Construction Detail (27 February 2008 Test)	
Component/Procedure	Mass (g)
Positive collector plus lead total metal mass including type K thermocouple wires Total positive lead mass including #69 Scotch tape and mica insulation was 0.655 g. SS ribbon was ~3 in. x ~0.110 in. wide by 0.003 in. thick.	0.343
Negative collector plus lead total metal mass including type K thermocouple wires Total negative lead mass including #69 Scotch tape and mica insulation was 0.529 g. SS ribbon was ~3 in. x ~0.110 in. wide by 0.003 in. thick.	0.344
Match metal total mass (0.370 in. long 0.003 in. diameter Nichrome bridge wire with ~5.1 in. long nickel leads each ~ 0.050 in. wide x 0.003 in. thick) – (2.9 ohm resistance at the nichrome wire ends and 3.4 ohm resistance at the nickel ribbon ends)	0.219
Fourteen 0.75 in. diameter blank 304 SS cell covers (0.0434 in. thick total)	2.429
Ten 0.75 in. diameter blank heat pellets	7.415
Nine 0.75 diameter blank anode pellets, Li/Al powder (90 mass % 20/80 Li/Al alloy, 10 mass % eutectic LiBr–LiCl–LiF electrolyte) that were never dried or heated above room temperature.	2.402
Nine 0.75 in. diameter blank E/C pellets – The nine E/C pellets lost 0.659% of their original mass while drying for 8 h and 43 min at 110 °C with the electronic cold trap in place and the vacuum oven open to the fore pump.	5.982
The E/C pellet chemical composition of the optimization program was calculated from 2228 June 8 2007 13:10 ec47L.for. The E/C of ec47L.for used a 34/66 sep/cat weight ratio and a 53/47 E/B weight ratio. The actual E/C construction target weights for GPS9T were 0.222 g separator, 0.445 g cathode, and 0.667 g E/C. The actual E/B ratio used in the GPS9T cathode was 55/45 because that powder was already processed and available.	
Positive lead electrical insulation 0.655-0.343	0.312
Negative lead electrical insulation 0.529-0.344	0.185
Begin mandrel assembly here on the bottom 0.75 in. diameter steel rod. Components are added in the order shown below.	
0.75 in. diameter blank mica disk 0.0039 in. thick with 2 parallel #69 tape strips 2.25 in. long x ~0.09 in. wide x 0.006 in. thick total mass 0.144 g	0.144
0.75 in. diameter Microtherm disk 0.0888 in. thick with ~0.25 in. x ~0.25 in. through notch	0.183
ARL heat paper (3 strips, NBS 390 cal/g powder) one ~0.25 in. x ~0.4 in. and two ~0.25 in. x ~0.25 in. strips all ~0.025 – .030 in. individual thickness, total mass 0.166g (This heat paper was placed in notch of the 0.183 g Microtherm disk above.)	0.166
0.75 in. diameter blank mica disk 0.0043 in. thick	0.089
0.75 in. diameter blank Microtherm disk 0.0871 in. thick	0.202
Negative current collector plus lead described above	0.529

Begin cell stack assembly (nine thermal cells, 10 heat pellets, 14 SS disks, nine anodes, nine electrolyte-cathode double layer pellets) here with negative lead and complete cell stack assembly here with positive lead. There are three SS disks between the cell stack and each of the stack end heat pellets. The positive and negative current collectors with their spot-welded type K thermocouples and SS lead ribbons attached are on the outer ends of the cell stack after the end heat pellets with the lead wires welded to the sides facing the thermal insulation. After the cell stack assembly is complete, continue with 0.75 in. diameter thermal insulation and heat paper to complete the mandrel assembly.	
Positive current collector plus lead described above	0.655
0.75 in. diameter blank Microtherm Disk 0.0864 in. thick	0.208
0.75 in. diameter blank Microtherm Disk 0.0878 in. thick	0.238
0.75 in. diameter blank SS disk 0.0032 in. thick	0.169
0.75 in. diameter blank heat paper disk 375 cal/g 0.0212 in. thick	0.182
0.75 in. diameter mica disk 0.0042 in. thick with 0.25 in. x ~0.25 in. through notch	0.070
0.75 in. diameter Microtherm disk 0.0885 in. thick with ~0.25 in. x ~0.25 in. through notch Placed the 0.204 g Microtherm disk on the 0.070 g mica disk so the notches lined up.	0.204
2 heat paper pieces ~0.25 in. x ~0.25 in. and one heat paper piece ~0.40 in. x ~0.25 in. of individual thicknesses ~0.0235 in. – 0.0260 in. Total mass 0.164 g of 390 cal/g heat powder heat paper placed into Microtherm notch with the ~0.4 in. x ~0.25 in. piece directly against the 0.182 g heat paper disk.	0.164
0.75 in. diameter blank mica disk 0.0048 in. thick with 2 parallel #69 Scotch tape strips each ~2.25 in. long x ~0.09 in. wide x 0.006 in. thick. Lined the four end tape strips on the top end of the mandrel assembly with the four #69 end tape strips on the bottom of the mandrel assembly.	0.153
Mandrel assembly is now complete.	
Compressed cell stack under 170 lb force with an 0.75 in. diameter steel rod at dew point –63.1 ºC and removed the many chips with Accuwipes, forceps, scriber magnet, plug in light, and vacuum cleaner. About 80% of the chips were magnetic (heat pellet chips).	
Thermal cell stack fuse strip (388 cal/g heat paper ~1.245 in. x ~0.24 in. x ~0.015 in.	0.083
Discard excess NBS 390 c/g heat powder heat paper	0.015
Discard excess 375 c/g heat powder paper (~5% Microtherm by weight) 0.007x.95=.0665	0.007
Mica-tape fuse strip backing (mica is ~1.3 in. x ~0.21 in. x ~0.0038 in. and 0.045 g) Use ~3.0 in. x ~0.20 in. x 0.006 in. #69 Scotch electrical tape to hold mica in place by taping backing to steel rods (total mica – tape mass is 0.126 g).	0.126
Fiberfrax strip 970 °F ~2.54 in. – 2.57 in. x ~1.078 in. – 1.088 in. x ~0.0208 in. – 0.0218 in. (thickness measured by hand held micrometer)	0.451
Cut an internal slit for the positive lead and an external slit for the negative lead and taped the Fiberfrax strip around the cell diameter with the smooth surface of the Fiberfrax facing the cells. Used the eight #69 Scotch tape end strips on the mica disks at the two mandrel ends to tape the Fiberfrax wrap in place.	
~7.0 in. of non-adhesive glass tape 0.410 g – add #69 Scotch electrical tape, one piece ~1.25 in. x ~0.15 in. x ~0.006 in. to each end of non-adhesive tape (total mass of the three 3 tapes is 0.476 g)	0.476
Cell stack height 0.805 in. – 0.810 in. @ 172 lb force	
Steel rod to steel rod distance 1.150 in. – 1.159 in. @ 172 lb force	
Flight case inner length 1.365 – 0.031 = 1.334 in.	
Header thickness was 0.124 in. Laser weld lip was 0.091 tall in.	
Flight case inner diameter 1.312-2 x 0.031 = 1.250 in.	
Header liner was mica and Scotch #365 tape of total thickness 0.0142 in.	
Internal length for battery construction was 1.334-0.091-0.0142 = 1.2288 in.	
Flight case total metal mass was 28.009 g	

Header total metal mass including eight spot-welded SS leads (each lead ~2.0" x ~0.100 in. x 0.003 in.) was 16.767 g	
Mica under positive lead ~1.34 in. x ~0.22 in. x 0.0038 in.	0.045
Taped the 0.045 g mica strip under positive lead with #69 Scotch tape.	
Taped the cell stack tightly between the + and – leads with the 0.476 g tape assembly.	
~8.5 in. of non-adhesive glass tape 0.509 g add #69 Scotch electrical tape one piece ~1.25 in. x ~0.15 in. x ~0.006 in. to each end of non-adhesive tape (total mass of the 3 tapes is 0.572 g)	0.572
Taped the positive and negative leads into place along the cell stack side with the 0.572 g tape assembly and added 0.033 g extra #69 Scotch electrical tape to hold the assembly in place.	0.033
Remove 0.048 g # 69 Scotch electrical tape that had been holding the fuse strip to the steel rods. Measure cell stack diameter at 0.794 in. to 0.845 in.	0.048
~17 in. of non-adhesive glass tape 1.018 g (added #69 Scotch electrical tape one piece ~2.00 in. x ~0.25 in. x 0.006 in. to each end of the non-adhesive tape) Total mass of the three tapes was 1.153g.	1.153
Inner Microtherm wrap ~2.88 in. x ~1.29 in. x ~0.032 in. (brown)	0.779
Inner heat paper wrap ~3.0 in. x ~1.39 in. x ~0.023 in. 375 cal/g paper	1.888
Outer Microtherm wrap ~3.12 in. x ~1.22 in. x ~0.086 in. (gray)	1.976
Outer heat paper wrap ~3.33 in. x ~1.39 in. x 0.025 in. 375 cal/g paper	2.128
There was no compression of any side wraps at all in the flight test batteries.	
Assembled the four side wrap pieces in sequence, increased the stack force to 194 lb with an 0.75 in. diameter steel rod, taped the ~17 in. non-adhesive glass tape to the non-adhesive tape already on the cell stack outer diameter with one of the #69 Scotch adhesive end tape strips, and taped all four side wraps to the cell stack side at once. Held the assembly in place using the adhesive strip on the other end of the non-adhesive strip. Then taped the entire outer diameter one time with #69 Scotch adhesive tape. The cell stack diameter then ranged from 1.145 in. to 1.210 in. (mostly 1.17 in. to 1.19 in.). Weighed the wrapped cell stack assembly at 30.941 g and then dried in vacuum at room temperature with an electronic cold trap in place.	30.941
Placed two blank mica disk bottom liners ~1.185 in. diameter x ~0.0061 in. total thickness into the bottom of the flight case (0.413 g total mass).	0.413
Placed a 375 cal/g blank heat paper disk ~1.25 in. diameter x ~0.023 in. thick on the two bottom mica liners.	0.563
Cut out the ~0.25 in. x ~0.25 in. notch in the positive end mica disk that covered the NBS heat paper fuse strip.	0.012
Removed heat paper from the positive stack end side wall area (~7% Microtherm by weight; .284x.93=.26412 g heat paper)	0.264
Removed heat paper from the negative stack end side wall area (~70% Microtherm by weight; .101x.3=.0303 g heat paper)	0.030
Cut away excess side wrap insulation and heat paper to bring the top of the side wall insulation and heat paper even with the top of the flight case with the 0.75 in. diameter stack under 185 lb force. Reweighed the cell stack at 30.295 g.	30.295
Cut out the ~0.25 in. x ~0.25 in. notch in the negative end mica disk that covered the NBS heat paper that will ignite the ~1.25 in. diameter bottom heat paper disk.	0.009
Scrubbed the negative end 0.75 in. diameter mica disk with Accuwipes and forceps and added two #69 Scotch tape strips of 0.063 g total mass. Each strip ~2.2 in. x ~0.09 in. x 0.006 in. was taped directly to one of the # 69 tape strips already on the 0.75 in. diameter mica disk. Both ends of the 2.2 in. long Scotch #69 tape strips protruded about equally past the negative end mica disk diameter.	0.063
Used 0.005 g Kapton tape to tape nickel match leads into place so that the nichrome wire was directly above the NBS heat paper in the ~0.25 in. x ~0.25 in. notch in the negative end mica tape assembly.	0.005

Placed a 375 cal/g heat paper disk ~0.75 in. diameter x ~0.0198 in. thick directly onto the top of the negative end mica-tape assembly.	0.172
Blank mica disk ~0.75 in. diameter by ~0.0049 in. thick	0.096
Shaved a blank Microtherm disk ~0.75 in. diameter to a ~0.065 in. thickness.	0.162
Bent the ~2.25 in. long #69 Scotch tape strips on the negative end mica disk over the top of the shaved 0.162 g Microtherm disk and taped them together adhesive side up.	
0.75 in. Diameter blank mica disk 0.0045 in. thick – placed directly on the exposed Scotch #69 tape adhesive	0.089
Added a stack of blank mica disks 0.75 in. diameter x 0.108 in. tall and applied 180 lb force to bring the top of the 0.108 in. tall mica stack to within 0.004 in. of the top of the 304 SS can flight case.	
Applied 180 lb force to the cell stack top with the 0.75 in. diameter steel rod. Insulated the electrical leads and covered the heat paper/insulation side wall with #69 Scotch tape with the cell stack under 180°lb force. Inserted mica strip ~4 in. x ~0.5 in. x ~0.0035 in. – 0.0036 in. into the case ID to insulate the lead wires from the case and removed 0.002 g of 375 c/g heat paper powder side wrap.	
Spot-welded leads, dried battery at room temperature overnight, and laser welded header into place. Cut away 0.710 g SS leads. The final header closing force was 400 pounds and the final battery mass after laser welding was 77.204 g. No external igniter or igniter housing was used.	

Appendix D. LCCM Thermal Optimization Program for the Enhanced 307 A–s Thermal Cell Stack

An input file, thermal optimization program, and output file for a thermal battery using the enhanced 307 A–s capacity LCCM thermal battery are shown in appendices D-1 through D-3. Six significant figures were used in most of the optimization calculations to assist in debugging the programs.

Most of the heat capacity data used in the optimization programs was reported to be accurate to better than 1% (*11*). Calorimetric and X-ray diffraction studies have shown that when 84/16 $Fe/KClO_4$ heat source is ignited, FeO is formed and 298 cal/g of the original $Fe/KClO_4$ powder are produced. FeO is defined in (*11*) as $Fe_{0.947}O$ with a molecular weight of 68.89 g for the heat capacity data that is reported there and that is used in the Fortran programs in this report.

For the present LCCM thermal battery, the side wall thermal insulation is so massive that sufficient axial 0.75 in. diameter heat pellets cannot simply be added to the cell stack ends. The additional heat pellets required at the stack ends would increase the transient and steady-state heat loss rates at the stack ends and overheat the end thermal cells, yet still leave large portions of the side wall thermal insulation between the battery top and bottom insufficiently heated. The volumetric heat capacity used for the thermal insulation package in the optimization program (0.752414 cal/cm^3) is an experimental value for a representative LCCM thermal battery that includes heat paper and electrical insulators such as mica and glass tape.

In the optimization program shown in appendix D-2, only the end thermal insulation and the thermal cell stack are heated by heat pellets. The side wall thermal insulation was heated by heat paper. Heating of the side wall thermal insulation is not included in the program calculations (the heat capacity of the side wall thermal insulation during the heating process was set to zero in the program), but heat paper in excess of the amount required to establish a steady-state temperature gradient in the side wall thermal insulation was used in the experimental batteries. Heat in excess of the amount required to establish a steady-state temperature gradient in the thermal insulation will be lost into the case rapidly and will have a small effect on the operating thermal battery lifetime. During cooling, the amount of heat yielded by the thermal insulation package is significant and has been included in this optimization program.

For the thermal batteries GPS9M and after (table 2), the heat required to establish a steady-state gradient in the end thermal insulation was actually supplied by heat paper rather than by heat pellets. After the thermal cells have been heated to their operating temperature, and a steady-state temperature gradient has been established in the thermal insulation, calculation of the cooling times are straightforward as outlined previously (1–9) and in the main report.

The overall estimate of the optimization calculation accuracies in the absence of detailed experimental battery operating data is estimated to be ±15%, primarily because of uncertainties in the temperature distributions and component positions in the operating batteries. Other Fortran programs in this appendix calculate the individual thermal cell maximum temperatures (D-4), the chemical compositions and densities of the combination electrolyte-cathode pellets (D-5), and the electrochemical capacities in A–s of the anodes and cathodes (D-6).

D-1. Input File

The numbers shown in the input file below may be identified under the NAMELIST printout HEREIN at the beginning of the output file. The straight line thermal conductivity estimate calculation is from a Microtherm brochure for a 60/40 H_2/N_2 mixture at one atmosphere of pressure in the porous Microtherm structure.

This is 239 30 April 2009 gntr1i in /home/fkrieger/fk/vk on heatu.

```
 435.       600.     –40.       60.
   7.86      4.2       1.509    3.17908
  3.14516    224.      112.
  3.16357   1.9050    .662940   .548640   .121771
  0.9202E-4  0.4056E-7   0.9202E-4   0.4056E-7
   1.009     0.0
```

D-2. Optimization Program

The optimization program shown below was written using the updated Fortran compiler as explained in section 5 of the main report. During the ATO program, a previous optimization program that gave identical numerical results required for battery construction was used to determine the battery construction parameters. The present program is altered only slightly from the original program and is more compatible with improved calculation techniques. Both programs use the input file shown in appendix D-2 to calculate values for the output file in appendix D-3. The program below calculates the optimal length for the thermal battery thermal cell and pyrotechnic stack along with the corresponding cooling time to TMINOP. A significant amount of pyrotechnic material must be added to heat the thermal insulation for optimal performance, and this program includes that amount of heat in the form of heat pellets added to the cell stack ends. The addition of sufficient heat to heat the side wall thermal insulation at the cell stack ends as heat pellets would cause the end thermal cells of this LCCM battery to overheat and fail, while leaving the side wall thermal insulation grossly under-heated. The heat required to heat the side wall thermal insulation was, therefore, added to the side wall insulation as heat paper in the experimental batteries. This program uses one uniform thermal conductivity value for all the materials (Microtherm, heat paper, glass tape, Fiberfrax and mica) that comprise the thermal insulation package. The axial and radial portions of the thermal insulation package can use different specific heats and thermal conductivity values.

This is 40378 April 30 2009 gntr1.for in /home/fkrieger/fk/vk on heatu.

```
C*****************************************************************
C                 This is the main program
C*****************************************************************

C     TMINOP =Minimum cell operating temperature  (C).
C     TMAXOP =Maximum cell operating temperature (C).
C     TAL    =Lowest ambient temperature (C).
C     TAH    =Highest  ambient  temperature  (C).
C     DENFE  =Density of iron (g/cm3).
C     DENHP  =Density of  heat pellet  (g/cm3).
C     DENA   =Density of anode (g/cm3).
C     DENEC  =Density of electrolyte-cathode (g/cm3).
C     FL3    =Inner length of outer case (cm).
C     HGF    =Total heat generated by thermal cells during first
C             cooling interval (cal).
C     HGB    =Total heat generated by thermal cells during second
C             cooling interval (cal).
C     D3     =Inner diameter of outer case (cm).
C     D2     =Outer diameter of heat reservoir (cm).
C     HEC    =Total height of electrolyte-cathodes (cm).
C     HA     =Total height of anodes (cm).
C     HFEST  =Total height of iron cell covers in stack (cm).
C     GK4,GB4=Thermal conductivity coefficients for end insulation.
C           K= GK4+GB4*TM, where K is thermal conductivity
C             (cal/sec-cm-C) and TM is the effective insulation
C             temperature TM=1/2(Tcell+Tcase) in degrees C.
C     GK5,GB5=Thermal conductivity coefficients for side insulation.
C     XPAN   =Thermal expansion factor for cells and reservoir
C             (dimensionless).
C     DH     =Diameter of center hole (cm).

      COMMON /SUBSTN/ FEHC,HPHC,AHC,ECHC
      COMMON /CALC/   PI,PQ,D2P,VEC,VA,VFEST,CHX,CA(6),CB(6),CC(6),
     1               CD(6),CE(6),CF(6),VHPST,HHPST,FL1,V1,P,FP,FI,
     2               FPE,FPS,VPIE,VPIS,CTX
      COMMON /DAT/    TMINOP,TMAXOP,TAL,TAH,D3,D2,GK4,GB4,END,SIDE,
     1               GK5,GB5,XPAN,DH,TIMEX,HGF,HGB
      COMMON /DNCITY/ DENFE,DENHP,DENA,DENEC
      COMMON /VERFY/  VFERS,VHPRS,FL2SV,FL3SV,VENDI,VSIDEI,CD1,CD2,CD3,
     1               CR1,CR2,CR3,TI1,TI2,TI3,TH1,TH2,TQM,RWX,RWY,R1,
     2               R2,R3,DT1,DT2,DT3,W1,W2,W3,T1,T2,T3
      NAMELIST/HERIN/ TMINOP,TMAXOP,TAL,TAH,DENFE,DENHP,DENA,DENEC,
     1               FL3,HGF,HGB,D2,D3,HEC,HA,HFEST,GK4,GB4,GK5,GB5,
     2               XPAN,DH
```

```
C
      OPEN(UNIT=5,NAME='/home/fkrieger/fk/vk/gntr1i',TYPE='OLD')
      OPEN(UNIT=6,NAME='/home/fkrieger/fk/vk/qfile',TYPE='NEW')
C
      READ(5,501) TMINOP,TMAXOP,TAL,TAH
      READ(5,501) DENFE,DENHP,DENA,DENEC
      READ(5,501) FL3,HGF,HGB
      READ(5,501) D3,D2,HEC,HA,HFEST
      READ(5,502) GK4,GB4,GK5,GB5
      READ(5,503) XPAN,DH
 501  FORMAT(8F10.5)
 502  FORMAT(4E12.3)
 503  FORMAT(2F10.5)
      WRITE(6,HERIN)
      PI=3.141592654
      PQ=PI/4.
      D2P=D2*D2-DH*DH
      VEC=PQ*D2P*HEC
      VA=PQ*D2P*HA
      VFEST=PQ*D2P*HFEST
      CHX=298.0*DENHP
      CALL MATERL(TAH,TMAXOP)
      CA(1)=ECHC
      CA(2)=FEHC
      CA(3)=HPHC
      CA(4)=AHC
      CA(5)=END
      CA(6)=SIDE
      CALL MATERL(TAL,TMINOP)
      CB(1)=ECHC
      CB(2)=FEHC
      CB(3)=HPHC
      CB(4)=AHC
      CB(5)=END
      CB(6)=SIDE
      CTX=CHX-CA(3)
      VHPST=(VEC*CA(1)+VFEST*CA(2)+VA*CA(4))/CTX
      HHPST=VHPST/(PQ*D2P)
      FL1=HEC+HA+HFEST+HHPST
      V1=PQ*D2P*FL1
      P=CA(2)/CTX
      FP=P/(P+1.0)
      FI=1.0-FP
      FPE=CA(5)/CTX
      FPS=CA(6)/CTX
      DEL=FL3-FL1
```

```
      TIMEX=1.0
      DO K=1,20
        FL2L=FL1+FLOAT(K-1)*.05*DEL
        FL2U=FL2L+.05*DEL
        DO J=1,10
          FL2=(FL2U+FL2L)*.5
          CALL CHEK(QI,FL2,FL3,T,0)
          IF(T.GE. TIMEX) THEN
            IF(QI.GE.-1.0) THEN
              TIMEX=T
              FL2SV=FL2
            END IF
          END IF

          IF(DFL2.GT..001) THEN
             FL2L=FL2
          ELSE IF(DFL2.LT.-.001) THEN
             FL2U=FL2
          ELSE
             CALL CHEK(QI,FL2,FL3,T,0)
          END IF

        END DO

        CALL CHEK(QI,FL2,FL3,T,0)
      END DO
      WRITE(6,2029) TQM
      L=2
      CALL CHEK(QI,FL2SV,FL3,T,L)
      FL3SV=FL3
      WRITE(6,675)
  675 FORMAT(15H STOP 1000      )
 2029 FORMAT('TQM= ',F12.6)
      CALL VER
  999 STOP
      END

      SUBROUTINE VER

C     This subroutine does not calculate cooling times, but arranges
C     results in order for rapid verification of the calculations.

      COMMON /SUBSTN/ FEHC,HPHC,AHC,ECHC
      COMMON /CALC/   PI,PQ,D2P,VEC,VA,VFEST,CHX,CA(6),CB(6),CC(6),
     1               CD(6),CE(6),CF(6),VHPST,HHPST,FL1,V1,P,FP,FI,
     2               FPE,FPS,VPIE,VPIS,CTX
```

```
      COMMON /DAT/    TMINOP,TMAXOP,TAL,TAH,D3,D2,GK4,GB4,END,SIDE,
     1               GK5,GB5,XPAN,DH,TIMEX,HGF,HGB
      COMMON /DNCITY/ DENFE,DENHP,DENA,DENEC
      COMMON /VERFY/ VFERS,VHPRS,FL2SV,FL3SV,VENDI,VSIDEI,CD1,CD2,CD3,
     1              CR1,CR2,CR3,TI1,TI2,TI3,TH1,TH2,TQM,RWX,RWY,R1,
     2              R2,R3,DT1,DT2,DT3,W1,W2,W3,T1,T2,T3

      DIMENSION HC(24)
      VIRON=VFEST+VFERS
      VHPLT=VHPST+VHPRS+VPIE+VPIS
      VH=     PI/4 *DH*DH*FL2SV
      VSUM= VEC+VA+VIRON+VHPLT+VH+VENDI+VSIDEI
      VTOTAL= PI/4 *D3*D3*FL3SV
      WRITE(6,1001) VEC, VA, VIRON, VHPLT, VH, VENDI, VSIDEI, VSUM,
     1             VTOTAL
 1001 FORMAT(
     1'                COOLING  TIME  VERIFICATION                '/
     2' The results  for the  maximum  calculated  cooling time  are'/
     3' arranged below for  rapid verification  of the heat transfer'/
     4' calculations.                                        '/
     5                                                     /
     6' 1. Volume Check                                  '          /
     7'     a. Electrolyte-cathode               VEC    =',F12.7    /
     8'     b. Anode                           VA     =',F12.7    /
     9'     c. Iron                     VFEST + VFERS  =',F12.7    /
     1'     d. Heat pellet     VHPST + VHPRS +VPIE +VPIS =',F12.7    /
     2'     e. Center hole            (PI/4*DH*DH*FL2SV) =',F12.7    /
     3'     f. Insulation                               '          /
     4'             Volume end insulation =    VENDI   =',F12.7    /
     5'             Volume side insulation=    VSIDEI  =',F12.7    /
     6                                                     /
     7'     g. Total Volume  (Sum of a to g, above)      =',F12.7    /
     8'     i. Total Volume (from case dimensions)       '          /
     9'                (PI/4 *D3*D3*FL3SV) =    VTOTAL =',F12.7   //)

      HC(1)=  VEC   *  CA(1)
      HC(2)=  VA    *  CA(4)
      HC(3)=  VIRON *  CA(2)
      HC(4)=  VHPLT *  CA(3)
      HC(5)=  VENDI *  CA(5)
      HC(6)=  VSIDEI*  CA(6)
      SUM2 =  HC(1)+HC(2)+HC(3)+HC(4)+HC(5)+HC(6)
      CALC =  CHX   *  VHPLT
      WRITE(6,1002) VEC, CA(1),HC(1),VA,CA(4),HC(2),VIRON,CA(2),HC(3),
     1             VHPLT, CA(3), HC(4),VENDI,CA(5),HC(5),VSIDEI,
     2             CA(6),HC(6),SUM2, CALC
```

```
1002 FORMAT(
   1' 2. Heat Balance (TAH to TMAXOP)                              '/
   2                                                     /
   3'    Component',10X,'Volume',10X,'Ht. Cap.',9X,'Ht. Content  '/
   4'                   (cm3)',11X,'(cal/cm3)',10X,'(cal)    '/
   5                                                     /
   6'   Elec-cathode    ',F12.7,   6X,  F10.6,   7X,    F12.6    /
   7'   Anode           ',F12.7,   6X,  F10.6,   7X,    F12.6    /
   8'   Iron            ',F12.7,   6X,  F10.6,   7X,    F12.6    /
   1'   Heat Pellet     ',F12.7,   6X,  F10.6,   7X,    F12.6    /
   2'   End Insulation  ',F12.7,   6X,  F10.6,   7X,    F12.6    /
   3'   Side Insulation ',F12.7,   6X,  F10.6,   7X,    F12.6    /
   4'                                  ',17X, '---------   '/
   5'                              ',10X,'"SUM2"= ',F12.3   /
   6                                                     /
   7'   Heat Supplied = CHX * VHP =',F12.3                        /
   8'   (Heat Supplied should equal "SUM2")                     '//)

    HC(1)=  VEC   *  CC(1)
    HC(2)=  VA    *  CC(4)
    HC(3)=  VIRON *  CC(2)
    HC(4)=  VHPLT *  CC(3)
    HC(5)=  VENDI *  CC(5)
    HC(6)=  VSIDEI*  CC(6)
    SUM3 =  HC(1)+HC(2)+HC(3)+HC(4)+HC(5)+HC(6)
    WRITE(6,1003) VEC, CC(1),HC(1),VA,CC(4),HC(2),VIRON,CC(2),HC(3),
   1             VHPLT, CC(3), HC(4), VENDI, CC(5), HC(5),
   2             VSIDEI, CC(6), HC(6), SUM3
1003 FORMAT(
   1' 3. Heat Balance (TAL to TQM)                              '/
   2                                                     /
   3'    Component',10X,'Volume',10X,'Ht. Cap.',9X,'Ht. Content  '/
   4'                   (cm3)',11X,'(cal/cm3)',10X,'(cal)    '/
   5                                                     /
   6'   Elec-cathode    ',F12.7,   6X,  F10.6,   7X,    F12.6    /
   7'   Anode           ',F12.7,   6X,  F10.6,   7X,    F12.6    /
   8'   Iron            ',F12.7,   6X,  F10.6,   7X,    F12.6    /
   1'   Heat Pellet     ',F12.7,   6X,  F10.6,   7X,    F12.6    /
   2'   End Insulation  ',F12.7,   6X,  F10.6,   7X,    F12.6    /
   3'   Side Insulation ',F12.7,   6X,  F10.6,   7X,    F12.6    /
   2'                                  ',17X, '---------   '/
   3'                              ',10X,'"SUM3"= ',F12.3  //
   4'   ("SUM3" should equal "SUM2")                            '//)

    HC(1)=  VEC   *  CB(1)
    HC(2)=  VA    *  CB(4)
```

```
      HC(3)=  VIRON *  CB(2)
      HC(4)=  VHPLT *  CB(3)
      HC(5)=  VENDI *  CB(5)
      HC(6)=  VSIDEI*  CB(6)
      SUM4 =  HC(1)+HC(2)+HC(3)+HC(4)+HC(5)+HC(6)
      WRITE(6,1004) VEC, CB(1),HC(1),VA,CB(4),HC(2),VIRON,CB(2),HC(3),
     1          VHPLT, CB(3), HC(4), VENDI, CB(5), HC(5),
     2          VSIDEI, CB(6), HC(6), SUM4
 1004 FORMAT(
     1' 4. Heat Balance (TAL to TMINOP)                    '/
     2                                     /
     3'    Component',10X,'Volume',10X,'Ht. Cap.',9X,'Ht. Content  '/
     4'                  (cm3)',11X,'(cal/cm3)',10X,'(cal)    '/
     5                                     /
     6'   Elec-cathode    ',F12.7,   6X,  F10.6,   7X,    F12.6    /
     7'   Anode          ',F12.7,   6X,  F10.6,   7X,    F12.6    /
     8'   Iron           ',F12.7,   6X,  F10.6,   7X,    F12.6    /
     1'   Heat Pellet     ',F12.7,   6X,  F10.6,   7X,    F12.6    /
     2'   End Insulation  ',F12.7,   6X,  F10.6,   7X,    F12.6    /
     3'   Side Insulation ',F12.7,   6X,  F10.6,   7X,    F12.6    /
     2'                              ',17X, '---------   '/
     3'                           ',10X,'"SUM4"= ',F12.3  //)

      CD3E =  CD(5) / 2.
      CD3S=   CD(6) / 2.
      HC(1)=  VEC   *  CD(1)
      HC(2)=  VA    *  CD(4)
      HC(3)=  VIRON *  CD(2)
      HC(4)=  VHPLT *  CD(3)
      HC(5)=  VENDI *  CD3E
      HC(6)=  VSIDEI*  CD3S
      SUM5 =  HC(1)+HC(2)+HC(3)+HC(4)+HC(5)+HC(6)
      WRITE(6,1005) VEC, CD(1),HC(1),VA,CD(4),HC(2),VIRON,CD(2),HC(3),
     1          VHPLT, CD(3), HC(4), VENDI, CD3E, HC(5),
     2          VSIDEI, CD3S, HC(6), SUM5
 1005 FORMAT(
     1' 5. Heat Available (TH1 to TQM)                    '/
     2                                     /
     3'    Component',10X,'Volume',10X,'Ht. Cap.',9X,'Ht. Content  '/
     4'                  (cm3)',11X,'(cal/cm3)',10X,'(cal)    '/
     5                                     /
     6'   Elec-cathode    ',F12.7,   6X,  F10.6,   7X,    F12.6    /
     7'   Anode          ',F12.7,   6X,  F10.6,   7X,    F12.6    /
     8'   Iron           ',F12.7,   6X,  F10.6,   7X,    F12.6    /
     1'   Heat Pellet     ',F12.7,   6X,  F10.6,   7X,    F12.6    /
     2'   End Insulation  ',F12.7,   6X,  F10.6,   7X,    F12.6    /
```

```
   3'   Side Insulation ',F12.7,   6X,  F10.6,   7X,    F12.6     /
   2'                               ',17X, '---------   '/
   3'                            ',10X,'"SUM5"= ',F12.6  //)

    CD3E =  CE(5) / 2.
    CD3S =  CE(6) / 2.
    HC(1)=  VEC   *  CE(1)
    HC(2)=  VA    *  CE(4)
    HC(3)=  VIRON *  CE(2)
    HC(4)=  VHPLT *  CE(3)
    HC(5)=  VENDI *  CD3E
    HC(6)=  VSIDEI*  CD3S
    SUM6 =  HC(1)+HC(2)+HC(3)+HC(4)+HC(5)+HC(6)
    WRITE(6,1006) VEC, CE(1),HC(1),VA,CE(4),HC(2),VIRON,CE(2),HC(3),
   1          VHPLT, CE(3), HC(4), VENDI, CD3E, HC(5),
   2          VSIDEI, CD3S, HC(6), SUM6
1006 FORMAT(
   1' 6. Heat Available (TH2 to TH1)                        '/
   2                                              /
   3'    Component',10X,'Volume',10X,'Ht. Cap.',9X,'Ht. Content  '/
   4'                 (cm3)',11X,'(cal/cm3)',10X,'(cal)    '/
   5                                              /
   6'   Elec-cathode    ',F12.7,   6X,  F10.6,   7X,    F12.6     /
   7'   Anode         ',F12.7,   6X,  F10.6,   7X,    F12.6     /
   8'   Iron          ',F12.7,   6X,  F10.6,   7X,    F12.6     /
   1'   Heat Pellet     ',F12.7,   6X,  F10.6,   7X,    F12.6     /
   2'   End Insulation  ',F12.7,   6X,  F10.6,   7X,    F12.6     /
   3'   Side Insulation ',F12.7,   6X,  F10.6,   7X,    F12.6     /
   2'                               ',17X, '---------   '/
   3'                            ',10X,'"SUM6"= ',F12.6  //)

    CD3E =  CF(5) / 2.
    CD3S =  CF(6) / 2.
    HC(1)=  VEC   *  CF(1)
    HC(2)=  VA    *  CF(4)
    HC(3)=  VIRON *  CF(2)
    HC(4)=  VHPLT *  CF(3)
    HC(5)=  VENDI *  CD3E
    HC(6)=  VSIDEI*  CD3S
    SUM7 =  HC(1)+HC(2)+HC(3)+HC(4)+HC(5)+HC(6)
    WRITE(6,1007) VEC, CF(1),HC(1),VA,CF(4),HC(2),VIRON,CF(2),HC(3),
   1          VHPLT, CF(3), HC(4), VENDI, CD3E, HC(5),
   2          VSIDEI, CD3S, HC(6), SUM7
1007 FORMAT(
   1' 7. Heat Available (TMINOP  to TH2)                       '/
   2                                              /
```

```
     3'     Component',10X,'Volume',10X,'Ht. Cap.',9X,'Ht. Content  '/
     4'                    (cm3)',11X,'(cal/cm3)',10X,'(cal)    '/
     5                                                 /
     6'    Elec-cathode    ',F12.7,   6X,  F10.6,   7X,    F12.6     /
     7'    Anode          ',F12.7,   6X,  F10.6,   7X,    F12.6     /
     8'    Iron           ',F12.7,   6X,  F10.6,   7X,    F12.6     /
     1'    Heat Pellet     ',F12.7,   6X,  F10.6,   7X,    F12.6     /
     2'    End Insulation  ',F12.7,   6X,  F10.6,   7X,    F12.6     /
     3'    Side Insulation ',F12.7,   6X,  F10.6,   7X,    F12.6     /
     2'                                   ',17X, '---------   '/
     3'                                ',10X,'"SUM7"= ',F12.6  //)


      WRITE(6,1008) GK4,GB4,GK5,GB5,TQM,TH1,TH2,TMINOP,TAH,TAL,
     1           TI3,CD3,CR3,TI2,CD2,CR2,TI1,CD1,CR1

 1008 FORMAT(
     1' 8.  Thermal conductivities (cal/sec-cm-C)                  '/
     2                                                 /
     3'     GK4 = ',E12.7,'   GB4 = ',E12.7,                        /
     4'     GK5 = ',E12.7,'   GB5 = ',E12.7,                        /
     5'     TQM = ',F7.3,' TH1 = ',F7.3,' TH2 = ',F7.3,' TMINOP = ',
     5         F7.3,/,'     TAH = ',F7.3,' TAL = ',F7.3          /
     6                                                 /
     7'    a. Curve top                                    '/
     8'       T3     = TQM - 0.5 * DTQ                             '/
     8'       TI3    = (T3 + TAL) * 0.5                            '/
     9'              = mean insulation temperature        = ',E12.7  /
     1'       KEND   = GK4 + GB4 * TI3 = CD3              = ',E12.7  /
     2'       KSIDE  = GK5 + GB5 * TI3 = CR3              = ',E12.7  /
     3                                                 /
     4'    b. Curve center                                 '/
     5'       T2     = T3- 1.0 * DTQ                             '/
     5'       TI2    = (T2 + TAL) * 0.5                            '/
     6'              = mean insulation temperature        = ',E12.7  /
     7'       KEND   = GK4 + GB4 * TI2 = CD2              = ',E12.7  /
     8'       KSIDE  = GK5 + GB5 * TI2 = CR2              = ',E12.7  /
     9                                                 /
     1'    c. Curve bottom                                 '/
     5'       T1     = T2- 1.0 * DTQ                             '/
     5'       TI1    = (T1 + TAL) * 0.5                            '/
     6'              = mean insulation temperature        = ',E12.7  /
     7'       KEND   = GK4 + GB4 * TI1 = CD1              = ',E12.7  /
     8'       KSIDE  = GK5 + GB5 * TI1 = CR1              = ',E12.7  /)

      WRITE(6,1009) RWX,RWY
```

```
1009 FORMAT(
   1'  9.  Geometric shape factors                              '/
   2                                                      /
   3'     END plus EDGES     RWX  = '                            /
   4'     PI*((D2*D2*XPAN**2/(FL3SV-XPAN*FL2SV)+1.08*D2 *XPAN)= ',
   5      F10.3,' (cm)'                                  //
   6'     SIDE      RWY = '                                 /
   7'     PI* 2.0 *FL2SV*XPAN/ALOG(D3/D2/XPAN)              = ',F10.6,
   8      ' (cm)'                                       //)

    DT3 = T3 - TAL
    DT2 = T2 - TAL
    DT1 = T1 - TAL
    WRITE(6,1010) DT3,DT2,DT1
1010 FORMAT(
   1' 10.  Temperature differences:                         '/
   2                                                      /
   3'    a. Curve top                                    '/
   4'       DT3 = T3 - TAL            = ',F7.3,
   5        ' C'                                         //
   6'    b. Curve center                                  '/
   7'       DT2 = T2 - TAL            = ',F7.3,
   8        ' C'                                         //
   9'    c. Curve bottom                                  '/
   1'       DT1 = T1 - TAL            = ',F7.3,
   2        ' C'                                         //)

    WRITE(6,1011) R3, R2, R1
1011 FORMAT(
   1' 11.  Heat loss rates:                              '/
   2                                                      /
   3'    a. Curve top                                    '/
   4'       R3  = RWX*DT3*CD3 + RWY*DT3*CR3            = ',F10.6,
   5        ' cal/sec'                                   //
   6'    b. Curve center                                  '/
   4'       R2  = RWX*DT2*CD2 + RWY*DT2*CR2            = ',F10.6,
   8        ' cal/sec'                                   //
   9'    c. Curve bottom                                  '/
   4'       R1  = RWX*DT1*CD1 + RWY*DT1*CR1            = ',F10.6,
   2        ' cal/sec'                                   //)

    SUMW = W1 + W2 + W3
    WRITE(6,1012) W3, W2, W1, SUMW, SUMW
1012 FORMAT(
   1' 12.  Cooling Times                                  '/
   2                                                      /
```

```
3'     The amount  of  heat  generated is  measured from  the '/
4'     cooling  curves  and  inserted into  the cooling  time '/
5'     equation  in  the  subroutine  CHEK.  Heat  generation '/
6'     rates  increase  with  temperature and  decrease  with '/
7'     time.                                       '/
1                                                 /
2'   a. Curve top            W3 = (Q3 +HGF )/R3 = ',F10.6,
3      ' sec'                                      //
4'   b. Curve center          W2 = (Q2 + HGB)/R2 = ',F10.6,
6      ' sec'                                      //
7'   c. Curve bottom           W1 = Q1/R1       = ',F10.6,
6      ' sec'                                      //
7'   d. Total                W1 + W2 + W3      = ',F10.6,
8      ' sec'                                       /
9'                                TIME = ',F10.6,
1      ' sec'                                      //
2'   (Sum of W1 + W2 + W3 should equal "TIME")              '//)


 HC(1)= (CA(1)-17.5326 * DENEC)/((TMAXOP-TAH)*DENEC)
 HC(2)= (CA(4)-7.02 * DENA)/((TMAXOP-TAH)*DENA)
 HC(3)= CA(2)/((TMAXOP-TAH)*DENFE)
 HC(4)= CA(3)/((TMAXOP-TAH)*DENHP)

 HC(5)= (CC(1)-17.5326 * DENEC)/((TQM-TAL)*DENEC)
 HC(6)= (CC(4)-7.02 * DENA)/((TQM-TAL)*DENA)
 HC(7)= CC(2)/((TQM-TAL)*DENFE)
 HC(8)= CC(3)/((TQM-TAL)*DENHP)

 HC(9)= (CB(1)-17.5326 * DENEC)/((TMINOP-TAL)*DENEC)
 HC(10)= (CB(4)-7.02 * DENA)/((TMINOP-TAL)*DENA)
 HC(11)= CB(2)/((TMINOP-TAL)*DENFE)
 HC(12)= CB(3)/((TMINOP-TAL)*DENHP)

 HC(13)= CD(1)/((TQM-TH1)*DENEC)
 HC(14)= CD(4)/((TQM-TH1)*DENA)
 HC(15)= CD(2)/((TQM-TH1)*DENFE)
 HC(16)= CD(3)/((TQM-TH1)*DENHP)

 HC(17)= CE(1)/((TH1-TH2)*DENEC)
 HC(18)= CE(4)/((TH1-TH2)*DENA)
 HC(19)= CE(2)/((TH1-TH2)*DENFE)
 HC(20)= CE(3)/((TH1-TH2)*DENHP)

 HC(21)= CF(1)/((TH2-TMINOP)*DENEC)
 HC(22)= CF(4)/((TH2-TMINOP)*DENA)
```

```
    HC(23)= CF(2)/((TH2-TMINOP)*DENFE)
    HC(24)= CF(3)/((TH2-TMINOP)*DENHP)

    WRITE(6,1013) HC(1), HC(2), HC(3), HC(4), HC(5),
   1          HC(6), HC(7), HC(8), HC(9), HC(10),
   2          HC(11),HC(12),HC(13),HC(14),HC(15),
   3          HC(16),HC(17),HC(18),HC(19),HC(20),
   4          HC(21),HC(22),HC(23),HC(24)
1013 FORMAT(
   1' 13.  Calculated specific heats  (cal/g-C)                 '/
   2                                           /
   3'     The   calculated   specific   heats  of   the  battery '/
   4'     components  (cal/g-C)   are  easily  recognizable  and '/
   5'     generally increase slightly with  temperature.   These '/
   6'     values  are  printed out  below  as  an aid to program '/
   7'     debugging.                                   '/
   7                                           /
   8'     a.  Specific heats (TAH to TMAXOP)                  '/
   9'        1. Electrolyte-cathode                    '/
   1'           (CA(1)-17.5326 * DENEC)/((TMAXOP-TAH)*DENEC) = ',
   2           F12.7                           //
   3'        2. Anode                             '/
   4'           (CA(4)-7.02 * DENA)/((TMAXOP-TAH)*DENA)   = ',
   5           F12.7                           //
   6'        3. Iron                             '/
   7'           CA(2)/((TMAXOP-TAH)*DENFE)               = ',
   8           F12.7                           //
   3'        4. Heat Pellet                       '/
   4'           CA(3)/((TMAXOP-TAH)*DENHP)               = ',
   5           F12.7                           //
   6'     b.  Specific heats (TAL to TQM)                  '/
   8                                           /
   9'        1. Electrolyte-cathode                    '/
   1'           (CC(1)-17.5326 * DENEC)/((TQM-TAL)*DENEC)    = ',
   2           F12.7                           //
   3'        2. Anode                             '/
   4'           (CC(4)-7.02 * DENA)/((TQM-TAL)*DENA)      = ',
   5           F12.7                           //
   6'        3. Iron                             '/
   7'           CC(2)/((TQM-TAL)*DENFE)                  = ',
   8           F12.7                           //
   3'        4. Heat Pellet                       '/
   4'           CC(3)/((TQM-TAL)*DENHP)                  = ',
   5           F12.7                           //
   6'     c.  Specific heats (TAL to TMINOP)                 '/
   8                                           /
```

```
9'      1. Electrolyte-cathode                    '/
1'         (CB(1)-17.5326 * DENEC)/((TMINOP-TAL)*DENEC) = ',
2          F12.7                            //
3'      2. Anode                            '/
4'         (CB(4)-7.02 * DENA)/((TMINOP-TAL)*DENA)   = ',
5          F12.7                            //
6'      3. Iron                           '/
7'         CB(2)/((TMINOP-TAL)*DENFE)                = ',
8          F12.7                            //
3'      4. Heat Pellet                       '/
4'         CB(3)/((TMINOP-TAL)*DENHP)                = ',
5          F12.7                            //
6'    d.  Specific heats (TQM to TH1)                '/
7                                          /
8'      1. Electrolyte-cathode                    '/
9'         CD(1)/((TQM-TH1)*DENEC)                  = ',
1          F12.7                            //
2'      2. Anode                            '/
3'         CD(4)/((TQM-TH1)*DENA)                   = ',
4          F12.7                            //
5'      3. Iron                           '/
6'         CD(2)/((TQM-TH1)*DENFE)                  = ',
7          F12.7                            //
2'      4. Heat Pellet                       '/
3'         CD(3)/((TQM-TH1)*DENHP)                  = ',
4          F12.7                            //
5'    e.  Specific heats (TH1 to TH2)                '/
6                                          /
7'      1. Electrolyte-cathode                    '/
8'         CE(1)/((TH1-TH2)*DENEC)                  = ',
9          F12.7                            //
1'      2. Anode                            '/
2'         CE(4)/((TH1-TH2)*DENA)                   = ',
3          F12.7                            //
4'      3. Iron                           '/
5'         CE(2)/((TH1-TH2)*DENFE)                  = ',
6          F12.7                            //
1'      4. Heat Pellet                       '/
2'         CE(3)/((TQ1-TH2)*DENHP)                  = ',
3          F12.7                            //
5'    f.  Specific heats (TH1 to TMINOP)              '/
6                                          /
7'      1. Electrolyte-cathode                    '/
8'         CF(1)/((TH2-TMINOP)*DENEC)               = ',
9          F12.7                            //
1'      2. Anode                            '/
```

```
     2'           CF(4)/((TH2-TMINOP)*DENA)                = ',
     3             F12.7                            //
     4'        3. Iron                              '/
     5'           CF(2)/((TH2-TMINOP)*DENFE)               = ',
     6             F12.7                            //
     1'        4. Heat Pellet                          '/
     2'           CF(3)/((TH2-TMINOP)*DENHP)               = ',
     3             F12.7                               )

      RETURN
      END
      SUBROUTINE MATERL(TLOW,THIGH)

C    This subroutine calculates the cal/cm3 values between TLOW and
C    THIGH for  iron, heat pellet, anode, electrolyte-cathode,  and
C    thermal insulation.

C  1= Fe      6= LiF(s)      11= LiCl(l)      16= Al(l)
C  2= FeO     7= LiF(l)      12= Li2O         17= Heat Pellet
C  3= KCl(s)  8= LiBr(s)     13= Li(s)        18= Anode
C  4= FeS2    9= LiBr(l)     14= Li(l)        19= Elec-Cathode
C  5= MgO    10= LiCl(s)     15= Al(s)        20=

C    PR1= Weight fraction Fe, FeO, KCl in burned heat pellet.
C    PR2= Weight fraction  LiF, LiBr, LiCl, Li, Al, in anode.
C    PR3= Weight fraction Fe, FeS2, MgO, LiF, LiBr, LiCl, in
C    electrolyte/cathode.
C    GMW= Gram molecular weights of first 16 substances.
C
C    703.15 K = 430 C = Melting point of LiF-LiBr-LiCl eutectic.
C    453.7  K = 180.55 C = Melting point of Lithium.
C    70.20 cal/g  = Heat of fusion of LiF-LiBr-LiCl eutectic.
C    17.5326 cal/g  = Heat of fusion of LiF-LiBr-LiCl eutectic in
C         electrolyte-cathode (70.2*(.O238872+.170860+.0550045
C         = 17.5326).
C    7.02 cal/g  = Heat of fusion of LiF-LiBr-LiCl eutectic in
C         anode (70.2*(.00956438+.0684120+.0220237)= 7.02).
C    70.2 x .1 = 7.02
C    All heat capacities calculated as sum of component
C    heat capacities.
C    Liquid lithium heat capacity used above 453.7 K.
C    T (K) = T (C) + 273.15


      COMMON /DAT/    TMINOP,TMAXOP,TAL,TAH,D3,D2,GK4,GB4,END,SIDE,
     1               GK5,GB5,XPAN,DH,TIMEX,HGF,HGB
```

```
      COMMON /SUBSTN/ FEHC,HPHC,AHC,ECHC
      COMMON /DNCITY/ DENFE,DENHP,DENA,DENEC
      DIMENSION PR1(16),PR2(16),PR3(16),GMW(16),DELH(20)

      DATA
     1 PR1/0.595687,0.318222,0.0861032,0.,0.,0.,0.,0.,0.,0.,0.,0.,0.,
     1 0.,0.,0./,
     2 PR2/0.,0.,0.,0.,0.,.00956438,0.,.0684120,0.,.0220237,0.,
     3     0.,0.18,0.,0.72,0./,
     4 PR3/0.0132193,0.,0.,0.515552,0.221478,.0238872,0.,.170860,0.,
     5     .0550045,0.,0.,0.,0.,0.,0./,
     6 GMW/55.85,68.89,74.56,119.98,40.32,25.94,25.94,86.86,86.86,
     7 42.40,42.40,29.88,6.940,6.940,26.98,26.98/

      T1=TLOW+273.15
      T2=THIGH+273.15
      DO  I=1,5
        DELH(I)=ENTG(T1,T2,I)/GMW(I)
      END DO
C       DELH(12) = ENTG(T1,T2,12)/GMW(12)

          IF(T2.LT.703.15) THEN
            DELH(6) = ENTG(T1,T2,6)/GMW(6)
            DELH(8) = ENTG(T1,T2,8)/GMW(8)
            DELH(10)= ENTG(T1,T2,10)/GMW(10)
          ELSE IF(T1.GT.703.15) THEN
            DELH(6) = ENTG(T1,T2,7)/GMW(7)
            DELH(8) = ENTG(T1,T2,9)/GMW(9)
            DELH(10)= ENTG(T1,T2,11)/GMW(11)
          ELSE
            DELH(6) = ENTG(T1,703.15,6)/GMW(6)
     1            + ENTG(703.15,T2,7)/GMW(7)
            DELH(8) = ENTG(T1,703.15,8)/GMW(8)
     1            + ENTG(703.15,T2,9)/GMW(9)
            DELH(10)= ENTG(T1,703.15,10)/GMW(10)
     1            + ENTG(703.15,T2,11)/GMW(11)
          END IF
          IF(T2.LT.453.7) THEN
            DELH(13)= ENTG(T1,453.7,13)/GMW(13)
          ELSE IF(T1.GT.453.7) THEN
            DELH(13)= ENTG(T1,T2,14)/GMW(14)
          ELSE
            DELH(13)= ENTG(T1,453.7,13)/GMW(13)
     1            + ENTG(453.7,T2,14)/GMW(14)
          END IF
          IF(T2.LT.932.0) THEN
```

```
        DELH(15)= ENTG(T1,T2,15)/GMW(15)
      ELSE IF(T1.GT.932.0) THEN
        DELH(15)= ENTG(T1,T2,16)/GMW(16)
      ELSE
        DELH(15)= ENTG(T1,932.0,15)/GMW(15)
     1             + ENTG(932.0,T2,16)/GMW(16)
      END IF

      DELH(17)=0.0
      DELH(18)=0.0
      DELH(19)=0.0

      DO J= 1,16
        DELH(17)=DELH(J)*PR1(J)+DELH(17)
        DELH(18)=DELH(J)*PR2(J)+DELH(18)
        DELH(19)=DELH(J)*PR3(J)+DELH(19)
      END DO

      FEHC=DELH(1)*DENFE
      HPHC=DELH(17)*DENHP
      AHC=DELH(18)*DENA
      ECHC=DELH(19)*DENEC
      IF((T1.LT.703.11) .AND. (T2.GT.703.19)) THEN
        ECHC=(DELH(19)+17.5326)*DENEC
        AHC=(DELH(18)+7.02)*DENA
      END IF
      END =(.1716+.00009867*((T2+T1)*.5))*.752414*(T2-T1)*.5
      SIDE=(.1716+.00009867*((T2+T1)*.5))*.0*(T2-T1)*.5
      RETURN
      END
      FUNCTION ENTG(T1,T2,J)
C     This function calculates the molar heat content between T1 and T2.
C     TR1, TR2, TR3 are molar heat capacity coefficients of the first
C     16 substances.

      DIMENSION TR1(16),TR2(16),TR3(16)
      DATA
     2 TR1/ 3.04, 11.66, 9.89, 17.88, 10.18, 10.41, 15.50, 11.50,
     3     16.00, 11.00, 16.00, 14.94, 1.64, 6.78, 4.94, 7.00/,
     4 TR2/ 0.00758, 0.002, 0.0052, 0.00132, .00174, 0.00390, 0.,
     5     0.00302, 0.0, .0034, 0.0, .00608, .0111, 0.0, .00296, 0.0/,
     6 TR3/ 60000., -67000., 77000.,-305000., -148000.,-138000., 0.,
     7     0., 0., 0., 0.,-338000., 84000., 99000., 0., 0./
      ENTG=(T2-T1)*TR1(J)+.5*(T2*T2-T1*T1)*TR2(J)-(1./T2-1./T1)*TR3(J)
      RETURN
      END
```

```
      SUBROUTINE CHEK(QI,FL2,FL3,TIME,L)

C     This subroutine calculates the cooling times for various FL2.

C     FL2 is the length of the cell  stack plus the thermal reservoir
C     and the heat pellet required to heat the thermal insulation  in
C     centimeters.

C     The case  temperature is assumed to  remain unchanged when  the
C     unit is  fired at  TAL.  The  calculations are  therefore valid
C     under worst case heat sink conditions.

      COMMON /VERFY/ VFERS,VHPRS,FL2SV,FL3SV,VENDI,VSIDEI,CD1,CD2,CD3,
     1          CR1,CR2,CR3,TI1,TI2,TI3,TH1,TH2,TQM,RWX,RWY,R1,
     2          R2,R3,DT1,DT2,DT3,W1,W2,W3,T1,T2,T3
      COMMON/SUBSTN/ FEHC,HPHC,AHC,ECHC
      COMMON /CALC/  PI,PQ,D2P,VEC,VA,VFEST,CHX,CA(6),CB(6),CC(6),
     1          CD(6),CE(6),CF(6),VHPST,HHPST,FL1,V1,P,FP,FI,
     2          FPE,FPS,VPIE,VPIS,CTX
      COMMON /DAT/    TMINOP,TMAXOP,TAL,TAH,D3,D2,GK4,GB4,END,SIDE,
     1           GK5,GB5,XPAN,DH,TIMEX,HGF,HGB
      NAMELIST /OUT/ TIMEX,W1,W2,W3,Q1,Q2,Q3,R1,R2,R3,RWX,RWY,TQM,DTQ,
     1          FL1,FL2SV,HHPST,TH1,TH2
      NAMELIST /RIP/ CA,CB,CC,CD,CE,CF,VOLINS,V2,VEC,VA,VFEST,VFERS,
     1          VHPST,VHPRS,FP,FI,CHX,CHXT,CD3,CR3,CD2,CR2,CD1,CR1,
     2          V3,VENDI,VSIDEI,PILE,PILS,VPIE,VPIS,V2P,THPV,TFEV,
     3          FPE,FPS

  331 V3=D3*D3*PQ*FL3
      V2=D2P*PQ*(FL2-FL1)
      VENDI=PQ*D3*D3*(FL3-FL2)
      VSIDEI=PQ*(D3*D3-D2*D2)*FL2
      VOLINS=VENDI+VSIDEI
      PILE=FPE*VENDI/(PQ*D2P)
      PILS=FPS*VSIDEI/(PQ*D2P)
      VPIE=PILE*PQ*D2P
      VPIS=PILS*PQ*D2P
      V2P=V2-VPIE-VPIS
      IF (V2P .LE. 0.) THEN
      DELC=FL3-FL1
      DO MN=1,39
      FL2=FL2+0.025*DELC
      GO TO 331
      END DO
      END IF
```

```
      V2=V2-VPIE-VPIS
      VHPRS=V2*FP
      VFERS=V2*FI
      THPV=VHPST+VHPRS+VPIE+VPIS
      TFEV=VFEST+VFERS
      CHXT=THPV*CHX
      TQL=TMINOP
      TQH=TMAXOP
C     TQM=  Maximum cell temperature reached from TAL.  Estimated
C           from 30 successive approximations.
      DO I= 1,30
        TQM=0.5*(TQL+TQH)
        CALL MATERL(TAL,TQM)
        CC(1)=ECHC
        CC(2)=FEHC
        CC(3)=HPHC
        CC(4)=AHC
        CC(5)=END
        CC(6)=SIDE
        QM= VEC*CC(1)+TFEV*CC(2)+THPV*CC(3)+VA*CC(4)+CC(5)*VENDI+
     1       CC(6)*VSIDEI
        QI= CHXT-QM
        IF(QI.LE.0.0) THEN
          TQH=TQM
        ELSE
          TQL=TQM
        END IF
      END DO
      DTQ=(TQM-TMINOP)/3.0
      T3=TQM-0.5*DTQ
      T2=T3-1.0*DTQ
      T1=T2-1.0*DTQ
      TI3=(T3+TAL)*0.5
      TI2=(T2+TAL)*0.5
      TI1=(T1+TAL)*0.5
      CD3=GK4+GB4*TI3
      CR3=GK5+GB5*TI3
      CD2=GK4+GB4*TI2
      CR2=GK5+GB5*TI2
      CD1=GK4+GB4*TI1
      CR1=GK5+GB5*TI1
      DT3=T3-TAL
      DT2=T2-TAL
      DT1=T1-TAL
      RWX=PI*(D2*D2*XPAN**2/(FL3-XPAN*FL2)+1.08*D2*XPAN)
      RWY=PI*2.0*FL2*XPAN/ALOG(D3/D2/XPAN)
```

```
      R3=RWX*DT3*CD3+RWY*DT3*CR3
      R2=RWX*DT2*CD2+RWY*DT2*CR2
      R1=RWX*DT1*CD1+RWY*DT1*CR1
      TH1=TQM-DTQ
      TH2=TH1-DTQ
      CALL MATERL(TH1,TQM)
      CD(1)=ECHC
      CD(2)=FEHC
      CD(3)=HPHC
      CD(4)=AHC
      CD(5)=(.1716+.00009867*((((TH1+273.15+TQM+273.15)*.5)+TAL+273.15)
     1*.5))*.752414*(TQM-TH1)
      CD(6)=(.1716+.00009867*((((TH1+273.15+TQM+273.15)*.5)+TAL+273.15)
     1*.5))*.752414*(TQM-TH1)
      Q3=VEC*CD(1)+TFEV*CD(2)+THPV*CD(3)+VA*CD(4)+CD(5)*VENDI/2.
     1  +CD(6)*VSIDEI/2.
C     HGF Calories are generated by the cells during W3
      W3=(Q3+HGF)/R3
      CALL MATERL(TH2,TH1)
      CE(1)=ECHC
      CE(2)=FEHC
      CE(3)=HPHC
      CE(4)=AHC
      CE(5)=(.1716+.00009867*((((TH1+273.15+TH2+273.15)*.5)+TAL+273.15)
     1*.5))*.752414*(TH1-TH2)
      CE(6)=(.1716+.00009867*((((TH1+273.15+TH2+273.15)*.5)+TAL+273.15)
     1*.5))*.752414*(TH1-TH2)
      Q2=VEC*CE(1)+TFEV*CE(2)+THPV*CE(3)+VA*CE(4)+CE(5)*VENDI/2.
     1 +CE(6)*VSIDEI/2.
C     HGB Calories are generated by the cells during W2
      W2=(Q2+HGB)/R2
      CALL MATERL(TMINOP,TH2)
      CF(1)=ECHC
      CF(2)=FEHC
      CF(3)=HPHC
      CF(4)=AHC
      CF(5)=(.1716+.00009867*((((TH2+273.15+TMINOP+273.15)*.5)+TAL+
     1 273.15)*.5))*.752414*(TH2-TMINOP)
      CF(6)=(.1716+.00009867*((((TH2+273.15+TMINOP+273.15)*.5)+TAL+
     1 273.15)*.5))*.752414*(TH2-TMINOP)
      Q1=VEC*CF(1)+TFEV*CF(2)+THPV*CF(3)+VA*CF(4)+CF(5)*VENDI/2.
     1  +CF(6)*VSIDEI/2.
      W1=Q1/R1
      TIME=W1+W2+W3
      IF(L.EQ.2) THEN
        WRITE(6,RIP)
```

```
   WRITE(6,OUT)
  END IF
  RETURN
  END
```

D-3. Output File

The source program calculates the length of the stack that produces the maximum cooling time from the input parameters provided. Once that stack length is known, all of the parameters required to construct the battery have either been calculated by the program or are specified in the input file. The output file below is then printed from the optimization program and shows the results arranged in a format suitable for rapid confirmation of the optimization calculations.

This is 14949 30 April 2009 gntr1o in /home/fkrieger/fk/vk on heatu.

```
&HERIN
 TMINOP =  435.,
 TMAXOP =  600.,
 TAL = -40.,
 TAH =  60.,
 DENFE =  7.86000013,
 DENHP =  4.19999981,
 DENA =  1.50899994,
 DENEC =  3.17908001,
 FL3 =  3.14515996,
 HGF =  224.,
 HGB =  112.,
 D2 =  1.90499997,
 D3 =  3.16356993,
 HEC =  0.662940025,
 HA =  0.548640013,
 HFEST =  0.121771,
 GK4 =  9.20199964E-05,
 GB4 =  4.05599998E-08,
 GK5 =  9.20199964E-05,
 GB5 =  4.05599998E-08,
 XPAN =  1.00899994,
 DH =  0./
TQM=   529.870361
&RIP
 CA =  388.51239  594.150757  356.313812  321.925812  46.9509811  0.,
 CB =  329.187134  465.997803  290.215057  271.272217  38.9632111  0.,
 CC =  389.073853  578.293091  354.862335  325.435486  47.299469  0.,
 CD =  20.0389137  38.3590164  21.9058552  18.1458549  5.01117373  5.01117373,
 CE =  19.9633656  37.4303246  21.5487995  18.0537663  4.97768641  4.97768641,
```

```
 CF =  19.8844147  36.5059204  21.1926365  17.963644  4.94419956  4.94419956,
 VOLINS =  18.7765503,
 V2 =  0.0961295962,
 VEC =  1.88953125,
 VA =  1.56375003,
 VFEST =  0.347075313,
 VFERS =  0.057782568,
 VHPST =  1.61259377,
 VHPRS =  0.0383470245,
 FP =  0.398909658,
 FI =  0.601090312,
 CHX =  1251.59998,
 CHXT =  2612.75586,
 CD3 =  0.000101553385,
 CR3 =  0.000101553385,
 CD2 =  0.000100944271,
 CR2 =  0.000100944271,
 CD1 =  0.000100335157,
 CR1 =  0.000100335157,
 V3 =  24.7222233,
 VENDI =  8.3251667,
 VSIDEI =  10.4513836,
 PILE =  0.153177828,
 PILS =  0.,
 VPIE =  0.436591983,
 VPIS =  0.,
 V2P =  0.0961295962,
 THPV =  2.08753276,
 TFEV =  0.404857874,
 FPE =  0.0524424314,
 FPS =  0./
&OUT
 TIMEX =  362.724091,
 W1 =  78.6974182,
 W2 =  122.692955,
 W3 =  161.33371,
 Q1 =  171.100403,
 Q2 =  172.822662,
 Q3 =  174.545151,
 R1 =  2.17415524,
 R2 =  2.32142639,
 R3 =  2.47031546,
 RWX =  17.6785278,
 RWY =  26.542181,
 TQM =  525.105835,
 DTQ =  30.0352783,
```

FL1 = 1.89912784,
FL2SV = 2.08603263,
HHPST = 0.565776765,
TH1 = 495.070557,
TH2 = 465.035278/
STOP 1000

COOLING TIME VERIFICATION

The results for the maximum calculated cooling time are arranged below for rapid verification of the heat transfer calculations.

1. Volume Check
   a. Electrolyte-cathode VEC = 1.8895313
   b. Anode VA = 1.5637500
   c. Iron VFEST + VFERS = 0.4048579
   d. Heat pellet VHPST + VHPRS +VPIE +VPIS = 2.0875328
   e. Center hole (PI/4*DH*DH*FL2SV) = 0.0000000
   f. Insulation
      Volume end insulation = VENDI = 8.3251667
      Volume side insulation= VSIDEI = 10.4513836

   g. Total Volume (Sum of a to g, above) = 24.7222214
   i. Total Volume (from case dimensions)
      (PI/4 *D3*D3*FL3SV) = VTOTAL = 24.7222233

2. Heat Balance (TAH to TMAXOP)

Component	Volume (cm3)	Ht. Cap. (cal/cm3)	Ht. Content (cal)
Elec-cathode	1.8895313	388.512390	734.106323
Anode	1.5637500	321.925812	503.411499
Iron	0.4048579	594.150757	240.546616
Heat Pellet	2.0875328	356.313812	743.816772
End Insulation	8.3251667	46.950981	390.874756
Side Insulation	10.4513836	0.000000	0.000000

		"SUM2"=	2612.756

Heat Supplied = CHX * VHP = 2612.756
(Heat Supplied should equal "SUM2")

3. Heat Balance (TAL to TQM)

Component	Volume (cm3)	Ht. Cap. (cal/cm3)	Ht. Content (cal)
Elec-cathode	1.8895313	389.073853	735.167175
Anode	1.5637500	325.435486	508.899750
Iron	0.4048579	578.293091	234.126511
Heat Pellet	2.0875328	354.862335	740.786743
End Insulation	8.3251667	47.299469	393.775970
Side Insulation	10.4513836	0.000000	0.000000

		"SUM3"=	2612.756

("SUM3" should equal "SUM2")

4. Heat Balance (TAL to TMINOP)

Component	Volume (cm3)	Ht. Cap. (cal/cm3)	Ht. Content (cal)
Elec-cathode	1.8895313	329.187134	622.009399
Anode	1.5637500	271.272217	424.201935
Iron	0.4048579	465.997803	188.662872
Heat Pellet	2.0875328	290.215057	605.833435
End Insulation	8.3251667	38.963211	324.375214
Side Insulation	10.4513836	0.000000	0.000000

		"SUM4"=	2165.083

5. Heat Available (TH1 to TQM)

Component	Volume (cm3)	Ht. Cap. (cal/cm3)	Ht. Content (cal)
Elec-cathode	1.8895313	20.038914	37.864155
Anode	1.5637500	18.145855	28.375582
Iron	0.4048579	38.359016	15.529950
Heat Pellet	2.0875328	21.905855	45.729191
End Insulation	8.3251667	2.505587	20.859428
Side Insulation	10.4513836	2.505587	26.186850

		"SUM5"=	174.545151

6. Heat Available (TH2 to TH1)

Component	Volume (cm3)	Ht. Cap. (cal/cm3)	Ht. Content (cal)
Elec-cathode	1.8895313	19.963366	37.721405
Anode	1.5637500	18.053766	28.231577
Iron	0.4048579	37.430325	15.153961
Heat Pellet	2.0875328	21.548800	44.983826
End Insulation	8.3251667	2.488843	20.720034
Side Insulation	10.4513836	2.488843	26.011854

		"SUM6"=	172.822662

7. Heat Available (TMINOP to TH2)

Component	Volume (cm3)	Ht. Cap. (cal/cm3)	Ht. Content (cal)
Elec-cathode	1.8895313	19.884415	37.572224
Anode	1.5637500	17.963644	28.090649
Iron	0.4048579	36.505920	14.779709
Heat Pellet	2.0875328	21.192636	44.240322
End Insulation	8.3251667	2.472100	20.580643
Side Insulation	10.4513836	2.472100	25.836863

		"SUM7"=	171.100403

8. Thermal conductivities (cal/sec-cm-C)

GK4 = .9202000E-04 GB4 = .4056000E-07
GK5 = .9202000E-04 GB5 = .4056000E-07
TQM = 525.106 TH1 = 495.071 TH2 = 465.035 TMINOP = 435.000
TAH = 60.000 TAL = -40.000

a. Curve top
T3 = TQM - 0.5 * DTQ
TI3 = (T3 + TAL) * 0.5
= mean insulation temperature = .2350441E+03
KEND = GK4 + GB4 * TI3 = CD3 = .1015534E-03
KSIDE = GK5 + GB5 * TI3 = CR3 = .1015534E-03

b. Curve center
T2 = T3- 1.0 * DTQ
TI2 = (T2 + TAL) * 0.5

= mean insulation temperature = .2200265E+03

KEND = GK4 + GB4 * TI2 = CD2 = .1009443E-03

KSIDE = GK5 + GB5 * TI2 = CR2 = .1009443E-03

c. Curve bottom

T1 = T2- 1.0 * DTQ

TI1 = (T1 + TAL) * 0.5

= mean insulation temperature = .2050088E+03

KEND = GK4 + GB4 * TI1 = CD1 = .1003352E-03

KSIDE = GK5 + GB5 * TI1 = CR1 = .1003352E-03

9. Geometric shape factors

END plus EDGES RWX =

PI*((D2*D2*XPAN**2/(FL3SV-XPAN*FL2SV)+1.08*D2 *XPAN)= 17.679 (cm)

SIDE RWY =

PI* 2.0 *FL2SV*XPAN/ALOG(D3/D2/XPAN) = 26.542181 (cm)

10. Temperature differences:

a. Curve top

DT3 = T3 - TAL = 550.088 C

b. Curve center

DT2 = T2 - TAL = 520.053 C

c. Curve bottom

DT1 = T1 - TAL = 490.018 C

11. Heat loss rates:

a. Curve top

R3 = RWX*DT3*CD3 + RWY*DT3*CR3 = 2.470315 cal/sec

b. Curve center

R2 = RWX*DT2*CD2 + RWY*DT2*CR2 = 2.321426 cal/sec

c. Curve bottom

R1 = RWX*DT1*CD1 + RWY*DT1*CR1 = 2.174155 cal/sec

12. Cooling Times

The amount of heat generated is measured from the cooling curves and inserted into the cooling time equation in the subroutine CHEK. Heat generation rates increase with temperature and decrease with time.

a. Curve top W3 = (Q3 +HGF)/R3 = 161.333710 sec

b. Curve center W2 = (Q2 + HGB)/R2 = 122.692955 sec

c. Curve bottom W1 = Q1/R1 = 78.697418 sec

d. Total W1 + W2 + W3 = 362.724091 sec
TIME = 362.724091 sec

(Sum of W1 + W2 + W3 should equal "TIME")

13. Calculated specific heats (cal/g-C)

The calculated specific heats of the battery components (cal/g-C) are easily recognizable and generally increase slightly with temperature. These values are printed out below as an aid to program debugging.

a. Specific heats (TAH to TMAXOP)
1. Electrolyte-cathode
(CA(1)-17.5326 * DENEC)/((TMAXOP-TAH)*DENEC) = 0.1938453

2. Anode
(CA(4)-7.02 * DENA)/((TMAXOP-TAH)*DENA) = 0.3820689

3. Iron
CA(2)/((TMAXOP-TAH)*DENFE) = 0.1399846

4. Heat Pellet
CA(3)/((TMAXOP-TAH)*DENHP) = 0.1571049

b. Specific heats (TAL to TQM)

1. Electrolyte-cathode
(CC(1)-17.5326 * DENEC)/((TQM-TAL)*DENEC) = 0.1855459

2. Anode
(CC(4)-7.02 * DENA)/((TQM-TAL)*DENA) = 0.3692105

3. Iron
CC(2)/((TQM-TAL)*DENFE) = 0.1301954

4. Heat Pellet
CC(3)/((TQM-TAL)*DENHP) = 0.1495136

c. Specific heats (TAL to TMINOP)

1. Electrolyte-cathode
(CB(1)-17.5326 * DENEC)/((TMINOP-TAL)*DENEC) = 0.1810849

2. Anode
(CB(4)-7.02 * DENA)/((TMINOP-TAL)*DENA) = 0.3636832

3. Iron
CB(2)/((TMINOP-TAL)*DENFE) = 0.1248153

4. Heat Pellet
CB(3)/((TMINOP-TAL)*DENHP) = 0.1454712

d. Specific heats (TQM to TH1)

1. Electrolyte-cathode
CD(1)/((TQM-TH1)*DENEC) = 0.2098655

2. Anode
CD(4)/((TQM-TH1)*DENA) = 0.4003654

3. Iron
CD(2)/((TQM-TH1)*DENFE) = 0.1624850

4. Heat Pellet
CD(3)/((TQM-TH1)*DENHP) = 0.1736518

e. Specific heats (TH1 to TH2)

1. Electrolyte-cathode
CE(1)/((TH1-TH2)*DENEC) = 0.2090743

2. Anode
CE(4)/((TH1-TH2)*DENA) = 0.3983336

3. Iron
CE(2)/((TH1-TH2)*DENFE) = 0.1585511

4. Heat Pellet
CE(3)/((TQ1-TH2)*DENHP) = 0.1708214

f. Specific heats (TH1 to TMINOP)

1. Electrolyte-cathode
CF(1)/((TH2-TMINOP)*DENEC) = 0.2082475

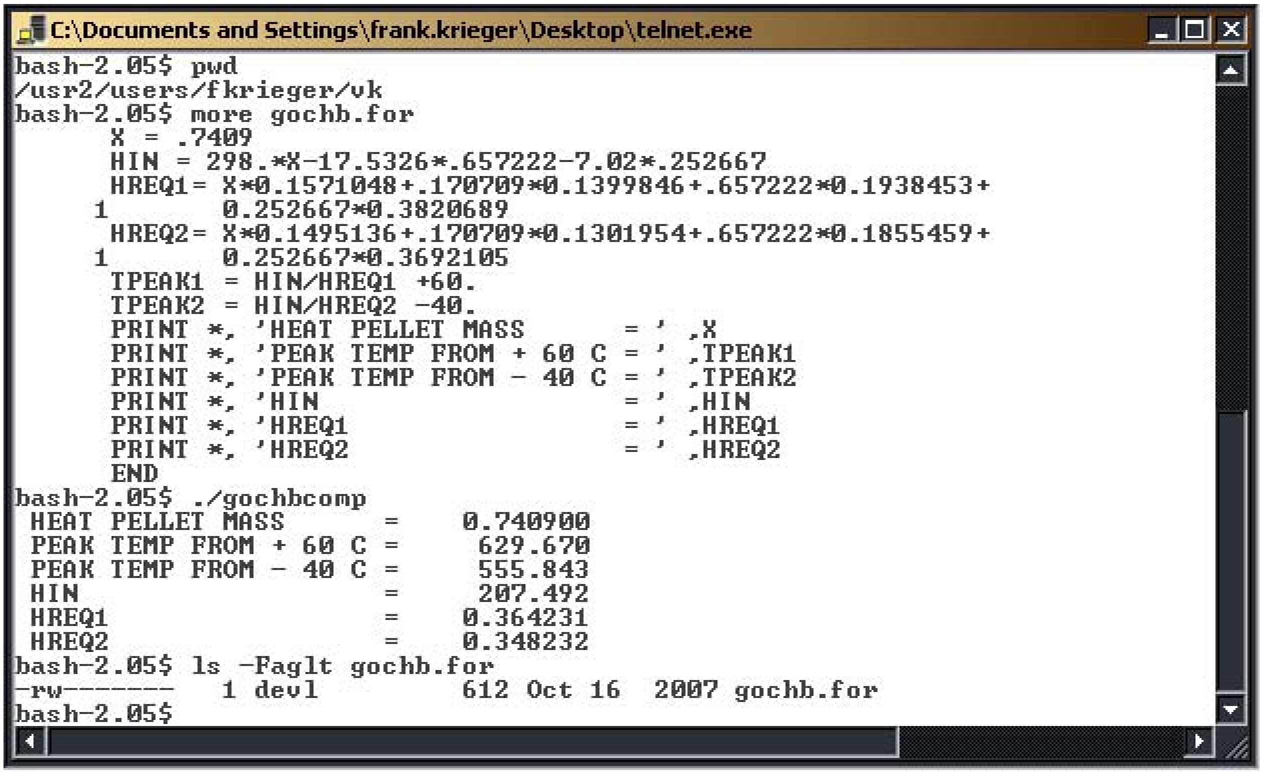
2. Anode
CF(4)/((TH2-TMINOP)*DENA) = 0.3963452

3. Iron
CF(2)/((TH2-TMINOP)*DENFE) = 0.1546355

4. Heat Pellet
CF(3)/((TH2-TMINOP)*DENHP) = 0.1679980

D-4. Individual Thermal Cell Maximum Temperatures

The Fortran program gochb.for shown below in picture format prints directly to the screen and is a representative program for calculating the maximum thermal cell temperatures in the thermal cell stack of the enhanced 307 A–s capacity enhanced LCCM thermal batteries. The program output values with the calculated maximum thermal cell temperatures when the battery is initiated at –40 ºC and at +60 ºC are also shown below. The heat capacities for the thermal cell components are taken from the Fortran outputs in appendix D-3 from TAH to TMAXOP and from TAL to TQM (see output item 13 [calculated specific heats cal/g-C] at the very end of the output file directly above this section). The maximum thermal cell temperature is calculated using only heat input from the heat pellets in the thermal cell stack. Experimental maximum thermal cell temperatures are usually 20 ºC to 40 ºC below such maximum calculated temperatures partly because of heat losses along the thermocouple wires near the thermocouple junction and partly because of heat losses into the thermal insulation shortly after battery initiation.



```
C:\Documents and Settings\frank.krieger\Desktop\telnet.exe
bash-2.05$ pwd
/usr2/users/fkrieger/vk
bash-2.05$ more gochb.for
      X = .7409
      HIN = 298.*X-17.5326*.657222-7.02*.252667
      HREQ1= X*0.1571048+.170709*0.1399846+.657222*0.1938453+
     1        0.252667*0.3820689
      HREQ2= X*0.1495136+.170709*0.1301954+.657222*0.1855459+
     1        0.252667*0.3692105
      TPEAK1  = HIN/HREQ1  +60.
      TPEAK2  = HIN/HREQ2  -40.
      PRINT *, 'HEAT PELLET MASS       = ' ,X
      PRINT *, 'PEAK TEMP FROM + 60 C = ' ,TPEAK1
      PRINT *, 'PEAK TEMP FROM - 40 C = ' ,TPEAK2
      PRINT *, 'HIN                   = ' ,HIN
      PRINT *, 'HREQ1                 = ' ,HREQ1
      PRINT *, 'HREQ2                 = ' ,HREQ2
      END
bash-2.05$ ./gochbcomp
 HEAT PELLET MASS      =    0.740900
 PEAK TEMP FROM + 60 C =     629.670
 PEAK TEMP FROM - 40 C =     555.843
 HIN                   =     207.492
 HREQ1                 =    0.364231
 HREQ2                 =    0.348232
bash-2.05$ ls -Faglt gochb.for
-rw-------    1 devl         612 Oct 16  2007 gochb.for
bash-2.05$
```

D-5. Electrolyte–Cathode Pellet Chemical Composition

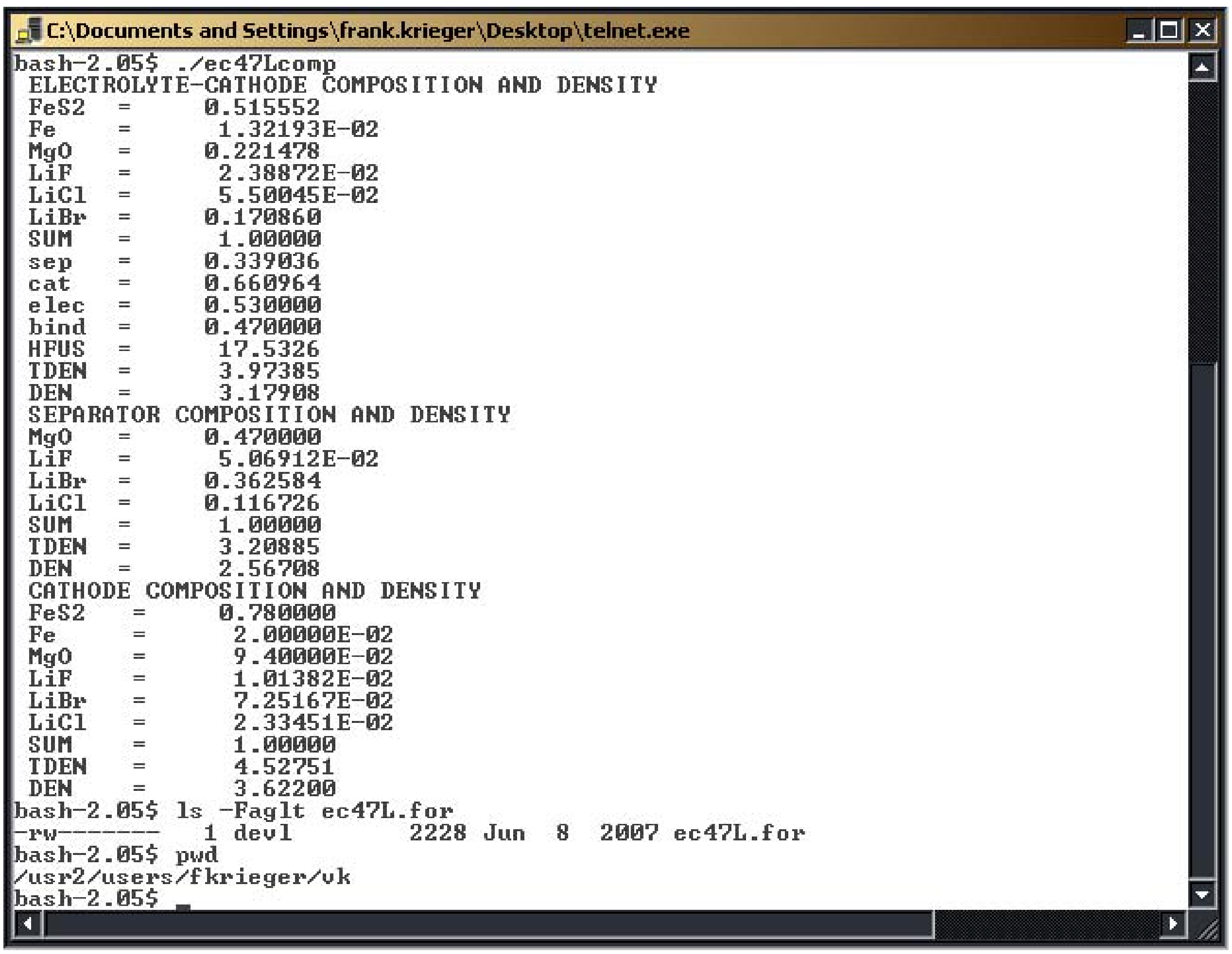
This Fortran program prints directly to the screen and was used to calculate the chemical compositions for the double layer electrolyte-cathode pellets for the enhanced 307 A–s capacity LCCM thermal battery in the thermal optimization program of appendix D-2. Chemical compositions from the program below are entered into SUBROUTINE MATERL of appendix D-2. Only four input variables (cat, sep, elec, and bind) need to be changed once the cathode and separator powders have been specified. Cat and sep are the weight ratios of the separator and cathode layers in the double layer E/C pellet. Elec and bind are the weight ratios of the electrolyte and binder in the separator layer. Separator powder (20 weight percent) is included in the cathode layer, and both layers are pressed to 80% of their theoretical density. A picture of the screen printout is included below for convenience.

This is 2228 June 8 2007 ec47L.for in /usr2/users/fkrieger/vk on push.

```
      sep=0.339036
      cat=0.660964
      elec=0.53
      bind=0.47
C     ELECTROLYTE-CATHODE COMPOSITION AND DENSITY
      FeS2=(0.78)*cat
```

```
      Fe=(0.02)*cat
      FMgO=sep*bind+cat*bind*0.2
      FLiF =(sep*elec+cat*elec*0.2)*0.0956438
      FLiBr=(sep*elec+cat*elec*0.2)*0.684120
      FLiCl=(sep*elec+cat*elec*0.2)*0.220237
      SUM  = FeS2+Fe+FMgO+FLiF+FLiBr+FLiCl
      HFUS = 70.2*(FLiF+FLiBr+FLiCl)
      TDEN =1./(FeS2/5.+Fe/7.86+FMgO/3.58+FLiF/2.635+FLiBr/3.464
     1        +FLiCl/2.068)
      DEN  =0.8*TDEN
      print *, 'ELECTROLYTE-CATHODE COMPOSITION AND DENSITY'
      print *, 'FeS2  =  ',FeS2
      print *, 'Fe    =  ',Fe
      print *, 'MgO   =  ',FMgO
      print *, 'LiF   =  ',FLiF
      print *, 'LiCl  =  ',FLiCl
      print *, 'LiBr  =  ',FLiBr
      print *, 'SUM   =  ',SUM
      print *, 'sep   =  ',sep
      print *, 'cat   =  ',cat
      print *, 'elec  =  ',elec
      print *, 'bind  =  ',bind
      print *, 'HFUS  =  ',HFUS
      print *, 'TDEN  =  ',TDEN
      print *, 'DEN   =  ',DEN
C     SEPARATOR COMPOSITION AND DENSITY
      FMGO =bind
      FLiF =elec*0.0956438
      FLiBr=elec*0.684120
      FLiCl=elec*0.220237
      SUM  =FMgO+FLiF+FLiBr+FLiCl
      TDEN =1./(FMgO/3.58+FLiF/2.635+FLiBr/3.464+FLiCl/2.068)
      DEN  =0.8*TDEN
      print *, 'SEPARATOR COMPOSITION AND DENSITY'
      print *, 'MgO   =  ',FMgO
      print *, 'LiF   =  ',FLiF
      print *, 'LiBr  =  ',FLiBr
      print *, 'LiCl  =  ',FLiCl
      print *, 'SUM   =  ',SUM
      print *, 'TDEN  =  ',TDEN
      print *, 'DEN   =  ',DEN
C     CATHODE COMPOSITION AND DENSITY
      FeS2=0.78
      Fe=0.02
      FMgO=bind*.2
      FLiF=elec*.0956438*.2
```

```
      FLiBr=elec*.684120*.2
      FLiCl=elec*.220237*.2
      SUM=FeS2+Fe+FMgO+FLiF+FLiBr+FLiCl
      TDEN=1./(FeS2/5.+Fe/7.86+FMgO/3.58+FLiF/2.635+FLiBr/3.464
     1 +FLiCl/2.068)
      DEN=0.8*TDEN
      print *, 'CATHODE COMPOSITION AND DENSITY'
      print *, 'FeS2   =  ',FeS2
      print *, 'Fe     =  ',Fe
      print *, 'MgO    =  ',FMgO
      print *, 'LiF    =  ',FLiF
      print *, 'LiBr   =  ',FLiBr
      print *, 'LiCl   =  ',FLiCl
      print *, 'SUM    =  ',SUM
      print *, 'TDEN   =  ',TDEN
      print *, 'DEN    =  ',DEN
      END
```



```
C:\Documents and Settings\frank.krieger\Desktop\telnet.exe
bash-2.05$ ./ec47Lcomp
 ELECTROLYTE-CATHODE COMPOSITION AND DENSITY
 FeS2  =     0.515552
 Fe    =      1.32193E-02
 MgO   =     0.221478
 LiF   =      2.38872E-02
 LiCl  =      5.50045E-02
 LiBr  =     0.170860
 SUM   =      1.00000
 sep   =     0.339036
 cat   =     0.660964
 elec  =     0.530000
 bind  =     0.470000
 HFUS  =      17.5326
 TDEN  =      3.97385
 DEN   =      3.17908
 SEPARATOR COMPOSITION AND DENSITY
 MgO   =     0.470000
 LiF   =      5.06912E-02
 LiBr  =     0.362584
 LiCl  =     0.116726
 SUM   =      1.00000
 TDEN  =      3.20885
 DEN   =      2.56708
 CATHODE COMPOSITION AND DENSITY
 FeS2    =     0.780000
 Fe      =      2.00000E-02
 MgO     =      9.40000E-02
 LiF     =      1.01382E-02
 LiBr    =      7.25167E-02
 LiCl    =      2.33451E-02
 SUM     =      1.00000
 TDEN    =      4.52751
 DEN     =      3.62200
bash-2.05$ ls -Faglt ec47L.for
-rw-------   1 devl        2228 Jun  8  2007 ec47L.for
bash-2.05$ pwd
/usr2/users/fkrieger/vk
bash-2.05$ _
```

D-6. Electrochemical Capacity of the Enhanced 307 A–s LCCM Battery Stack Anodes and Cathodes

During battery operation, past experience has shown that the thermal cells operate to 75% of their maximum voltage when 70% of the lithium and 55% of the FeS_2 has been depleted. The lithium aluminum alloy anodes are 20/80 weight percent Li/Al and the anodes contain 10% by weight electrolyte salt. Use 96489 coulombs/electrochemical equivalent for the Faraday constant and 6.939 g for the molecular weight of lithium. Then 96489x0.7/6.939 = 9733.72 A–s/g of lithium are available. The target weight of the anodes is 0.262 g so the anodes contain 0.262x0.2x0.9=0.04716 g lithium and can deliver 0.04716x9733.72=459.04 A–s of life to 75% of maximum voltage. The anodes were made thicker than was necessary to supply 307 A–s in order to avoid apparent self discharge from electrolyte flow during battery operation (See results for GPS9L in table 2 of the main report above).

The FeS_2 supplies 75% of the peak voltage after 55% of the electrochemical capacity has been used and each FeS_2 molecule supplies two electrons. The molecular weight of FeS_2 is 119.98 g, so there are 96489x2x0.55/119.98 = 884.630 A–s/g of FeS_2 available. The target weight of the cathode pellet is 0.445 g and the cathode is 78% FeS_2 by weight, so each cathode will supply 0.445x0.78x884.630=307.055 A–s to 75% of maximum voltage.

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Appendix E. Fortran Programs for Thermal Conductivity Values from LCCM Cooling Curves

Fortran programs used to calculate global thermal conductivity values of the thermal insulation packages from the experimental cooling curves of LCCM laboratory thermal batteries are shown in appendices E-1 through E-3. The source program in appendix E-1 calculates the global thermal conductivity values from digital data taken from the temperature-time curves. Appendix E-2 shows the output file for GPS9P operating under an internal fore pump vacuum of 7 Pa, and appendix E-3 shows the output file for GPS9Q operating under an internal gas pressure of 10.67 atmospheres. The same source program can be used for both GPS9P and GPS9Q because the batteries were constructed as identically as possible. Because GPS9P and GPS9Q were constructed as identically as possible, the only differences in electrochemical and thermal performances between GPS9P and GPS9Q should have been caused by the differences in the operating gas atmospheres.

The component masses used in this program are those measured while constructing GPS9Q. Heat contents of other thermal battery materials are included in the source program to facilitate its use in future experiments.

E-1. Source Program

This is 9567 March 24 2008 18:35 qcork2.for in /usr2/users/fkrieger/vk on push.

```
C  1= Fe      6= LiF(s)      11= LiCl(l)      16= Al(l)
C  2= FeO     7= LiF(l)      12= Li2O         17= Heat Pellet
C  3= KCl(s)  8= LiBr(s)     13= Li(s)        18= Anode
C  4= FeS2    9= LiBr(l)     14= Li(l)        19= Elec-Cathode
C  5= MgO     10=LiCl(s)     15= Al(s)        20= Eutectic

C     PR1= Weight fraction Fe, FeO, KCl in burned heat pellet.
C     PR2= Weight fraction LiF, LiBr, LiCl, Li, Al, in anode.
C     PR3= Weight fraction Fe, FeS2, MgO, LiF, LiBr, LiCl, in
C     electrolyte/cathode.
C     GMW= Gram molecular weights of first 16 substances.
C
C     703.15 K = 430 C = Melting point of LiF-LiBr-LiCl eutectic.
C     453.7  K = 180.55 C = Melting point of Lithium.
C     932 K = 658.85 C = Melting point of Aluminum.
C     70.20 cal/g  = Heat of fusion of LiF-LiBr-LiCl eutectic.
C     17.5326 cal/g  = Heat of fusion of LiF-LiBr-KBr eutectic in
C          electrolyte-cathode (70.20*(.0238872+.170860+.0550045)
C          = 17.5326).
```

```
C     7.02 cal/g  = Heat of fusion of LiF-LiBr-LiCl eutectic in
C     anode (70.2*(.00956438+.0684120+.0220237)=7.02) (Li(Al)).
C     The experimental cathode uses 45/55 E/B and anode uses only E.
C     The separator uses 53/47 E/B. The E/C composition was
C     calculated using 53/47 E/B for both separators and cathodes.
C     All heat capacities calculated as sum of component
C     heat capacities.
C     Liquid lithium heat capacity used above 453.7 K.
C     Liquid aluminum heat capacity used above 932 K.
C     Heat of fusion of lithium 715/6.94 = 103.026 c/g is ignored.
C     Heat of fusion of aluminum 2570/26.98 = 95.2557 c/g is ignored.
C     T (K) = T (C) + 273.15


      DIMENSION PR1(16),PR2(16),PR3(16),GMW(16),DELH(21)

      DATA
     1 PR1/0.595687,0.318222,0.0861032,0.,0.,0.,0.,0.,0.,0.,0.,0.,0.,
     1 0.,0.,0./,
     2 PR2/0.,0.,0.,0.,0.,.00956438,0.,.0684120,0.,.0220237,0.,
     3     0.,0.18,0.,0.72,0./,
     4 PR3/0.0132193,0.,0.,0.515552,0.221478,.0238872,0.,.170860,0.,
     5    .0550045,0.,0.,0.,0.,0.,0./,
     6 GMW/55.85,68.89,74.56,119.98,40.32,25.94,25.94,86.85,86.85,
     7 42.39,42.39,29.88,6.94,6.94,26.98,26.98/


      OPEN(UNIT=5,NAME='/usr2/users/fkrieger/vk/qk2i',TYPE='OLD')
      OPEN(UNIT=6,NAME='/usr2/users/fkrieger/vk/qfile',TYPE='NEW')
      READ(5,111) TI1,TT1,TB1,TC1
 8    READ(5,111,END=219) TI2,TT2,TB2,TC2
 111  FORMAT(F14.7,F17.7,F18.7,F17.7)
      THIGH=(TT1+TB1)/2.
      TLOW=(TT2+TB2)/2.
      TCASE=0.5*(TC1+TC2)
      TIME= TI2-TI1
      TM=(THIGH+TLOW)/2.
      TIN=(TM+TCASE)/2.
      T1=TLOW+273.15
      T2=THIGH+273.15
      DO  I=1,5
      IF((T2-T1).EQ.0.) GO TO 19
        DELH(I)=ENTG(T1,T2,I)/GMW(I)/(T2-T1)
      END DO

C     DELH(12) = ENTG(T1,T2,12)/GMW(12)
```

```
      IF(T2.LT.703.15) THEN
        DELH(6) = ENTG(T1,T2,6)/GMW(6)/(T2-T1)
        DELH(8) = ENTG(T1,T2,8)/GMW(8)/(T2-T1)
        DELH(10)= ENTG(T1,T2,10)/GMW(10)/(T2-T1)
      ELSE IF(T1.GT.703.15) THEN
        DELH(6) = ENTG(T1,T2,7)/GMW(7)/(T2-T1)
        DELH(8) = ENTG(T1,T2,9)/GMW(9)/(T2-T1)
        DELH(10)= ENTG(T1,T2,11)/GMW(11)/(T2-T1)
      ELSE
        DELH(6) = ENTG(T1,703.15,6)/GMW(6)/(T2-T1)
     1          + ENTG(703.15,T2,7)/GMW(7)/(T2-T1)
        DELH(8) = ENTG(T1,703.15,8)/GMW(8)/(T2-T1)
     1          + ENTG(703.15,T2,9)/GMW(9)/(T2-T1)
        DELH(10)= ENTG(T1,703.15,10)/GMW(10)/(T2-T1)
     1          + ENTG(703.15,T2,11)/GMW(11)/(T2-T1)
      END IF
      IF(T2.LT.453.7) THEN
        DELH(13)= ENTG(T1,T2,13)/GMW(13)/(T2-T1)
      ELSE IF(T1.GT.453.7) THEN
        DELH(13)= ENTG(T1,T2,14)/GMW(14)/(T2-T1)
      ELSE
        DELH(13)= ENTG(T1,453.7,13)/GMW(13)/(T2-T1)
     1          + ENTG(453.7,T2,14)/GMW(14)/(T2-T1)
      END IF
      IF(T2.LT.932.0) THEN
        DELH(15)= ENTG(T1,T2,15)/GMW(15)/(T2-T1)
      ELSE IF(T1.GT.932.0) THEN
        DELH(15)= ENTG(T1,T2,16)/GMW(16)/(T2-T1)
      ELSE
        DELH(15)= ENTG(T1,932.0,15)/GMW(15)/(T2-T1)
     1          + ENTG(932.0,T2,16)/GMW(16)/(T2-T1)
      END IF

      DELH(17)=0.0
      DELH(18)=0.0
      DELH(19)=0.0

      DO J=1,16
        DELH(17)=DELH(J)*PR1(J)+DELH(17)
        DELH(18)=DELH(J)*PR2(J)+DELH(18)
        DELH(19)=DELH(J)*PR3(J)+DELH(19)
      END DO

      DELH(20)=.0956438*DELH(6)+.684120*DELH(8)+.220237*DELH(10)
```

```
      CPHPAP = 0.14
      CPINS =.1716+.00009867*(TIN+273.15)
C     Expansion of the battery stack components with temperature.
      XPAN=1.+.1118E-4*(TM-23.)+.53E-8*(TM-23.)**2
      FL1=.765*2.54
      FL2=1.23825*2.54
      D1=0.75*2.54
      D2=1.2455*2.54
      PI=3.1415927
      RWX=PI*((D1*XPAN)**2/(FL2-FL1*XPAN)+1.08*D1*XPAN)
      RWY=PI*2.*FL1*XPAN/ALOG(D2/D1/XPAN)
      SHP=RWX+RWY

      XHC   = (T2-T1)*((3.223*DELH(1)+7.415*DELH(17)
     1+2.368*DELH(18)+5.958*DELH(19))+(CPHPAP*2.821+CPINS*9.465
     1+0.172*DELH(1))*.5)
      IF(THIGH.GT.430.01.AND.TLOW.LT.429.99) THEN
      TEUTFUS=7.02*1.570+17.5326*5.958
      XHC=XHC+TEUTFUS
      ELSE
      TEUTFUS=0.0
      END IF
      COND= XHC/(SHP*TIME*(TM-TCASE))
      AVTI= (TI1+TI2)/2.
      HLOSS= COND*SHP*(TM-TCASE)

      TSTHC = 3.223*(T2-T1)*DELH(1)
      THPHC = 7.415*(T2-T1)*DELH(17)
      TAHC  = 2.368*(T2-T1)*DELH(18)
      TECHC = 5.958*(T2-T1)*DELH(19)
      THPAPC= 2.821*(T2-T1)*.5*CPHPAP
      TINSHC= 9.465*(T2-T1)*.5*CPINS


      WRITE(6,220) THIGH,TLOW,DELH(1)
      WRITE(6,221) DELH(2),DELH(3),DELH(4)
      WRITE(6,222) DELH(5),DELH(13),DELH(15)
      WRITE(6,223) DELH(6),DELH(8),DELH(10)
      WRITE(6,224) DELH(17),DELH(18),DELH(19)
      WRITE(6,225) DELH(20),XHC
      WRITE(6,231) CPINS,CPHPAP
      WRITE(6,250) TSTHC,THPHC
      WRITE(6,251) TECHC,TINSHC
      WRITE(6,252) TAHC,THPAPC
      WRITE(6,235) T1,T2,TEUTFUS
      WRITE(6,232) COND,TM,TIN
```

```
      WRITE(6,233) TI1,TI2
      WRITE(6,237) TC1,TC2
      WRITE(6,236) HLOSS,AVTI
      WRITE(6,242) XHC,XPAN
      WRITE(6,243) RWX,RWY,SHP


 19   TI1=TI2
      TT1=TT2
      TB1=TB2
      TC1=TC2
      GO TO 8
 219  WRITE(6,226)
      WRITE(6,227)
      WRITE(6,228)
      WRITE(6,229)
 220  FORMAT(' THIGH=' ,F9.4,' TLOW=',F9.4,' Fe=', F12.7)
 221  FORMAT(' FeO=' ,F12.7,' KCl=',F12.7,' FeS2=', F12.7)
 222  FORMAT(' MgO=' ,F12.7,' Li=' ,F12.7,' Al=', F12.7)
 223  FORMAT(' LiF=', F12.7,' LiBr=',F12.7,' LiCl=', F12.7)
 224  FORMAT(' HPHC=', F12.7,' AHC=',F12.7,' ECHC=', F12.7)
 225  FORMAT(' EUT=' ,F12.7, ' XHC=',F15.5)
 226  FORMAT(' HFUSEC = 17.5326  HFUSA = 7.02  HFUSEUT = 70.2')
 227  FORMAT(' ECMASS = 5.958  ANODEMASS = 2.368')
 228  FORMAT(' HPELLETMASS = 7.415  STEELSTACKMASS = 3.223')
 229  FORMAT(' INSMASS = 9.465 HEAT PAPER MASS =2.821')
 231  FORMAT(' CPINS=' ,F12.7, ' CPHPAP=' , F12.4)
 232  FORMAT(' K=' ,F13.10,  ' TAVSTACK= ' ,F12.5, '  TAVINS= ' ,F12.5)
 233  FORMAT(' TIME1=' ,F12.5, ' TIME2= ' ,F12.5)
 235  FORMAT(' T1=' ,F12.6,  ' T2= ' ,F12.6, '  TEUTFUS= ' ,F12.6//)
 236  FORMAT(' HLOSS= ' ,F12.6, ' AVTIME = ' , F12.6)
 237  FORMAT(' TINICASE = ' ,F12.6, ' TFINCASE = ' ,F12.6)
 242  FORMAT(' XHC= ',F12.6,'  XPAN= ',F12.8)
 243  FORMAT(' RWX= ',F15.6,' RWY= ',F15.6,' SHP= ',F15.6//)

 250  FORMAT(' TSTHC=' ,F15.5, ' THPHC=',F15.5)
 251  FORMAT(' TECHC=' ,F15.5, ' TINSHC=',F15.5)
 252  FORMAT(' TAHC=' ,F15.5,  ' THPAPC=',F15.5)

 999  CONTINUE
      END

      FUNCTION ENTG(T1,T2,J)
C     This function calculates the molar heat content between T1 and T2.
C     TR1, TR2, TR3 are molar heat capacity coefficients of the first
C     16 substances.
```

```
      DIMENSION TR1(16),TR2(16),TR3(16)
      DATA
     2 TR1/ 3.04, 11.66, 9.89, 17.88, 10.18, 10.41, 15.50, 11.50,
     3      16.00, 11.00, 16.00, 14.94, 1.64, 6.78, 4.94, 7.00/,
     4 TR2/ 0.00758, 0.002, 0.0052, 0.00132, .00174, 0.00390, 0.,
     5      0.00302, 0., .0034, 0., .00608, .0111, 0., .00296, 0./,
     6 TR3/ 60000., -67000., 77000.,-305000.,-148000.,-138000., 0.,
     7      0., 0., 0., 0.,-338000., 84000., 99000., 0., 0./
      ENTG=(T2-T1)*TR1(J)+.5*(T2*T2-T1*T1)*TR2(J)-(1./T2-1./T1)*TR3(J)
      RETURN
      END
```

E-2. GPS9P (7 Pa Operating Atmospheric Pressure) Output File

This is 10140 4 March 2008 18:30 pk2o in /usr2/users/fkrieger/vk on push.

```
 THIGH= 546.2145 TLOW= 525.1410 Fe=   0.1658486
 FeO=   0.1912501 KCl=   0.1906333 FeS2=   0.1540370
 MgO=   0.2817731 Li=   0.9987543 Al=   0.2718357
 LiF=   0.5975327 LiBr=   0.1842257 LiCl=   0.3774475
 HPHC=   0.1760679 AHC=   0.4021286 ECHC=   0.2105245
 EUT=   0.2663107 XHC=      112.00765
 CPINS=   0.2231098 CPHPAP=      0.1400
 TSTHC=       11.26441 THPHC=       27.51236
 TECHC=       26.43258 TINSHC=       22.25080
 TAHC=       20.06703 THPAPC=        4.16138
 T1=  798.291016 T2=   819.364502  TEUTFUS=     0.000000


 K= 0.0024047464 TAVSTACK=    535.67773  TAVINS=    248.89062
 TIME1=     2.07800 TIME2=      4.06700
 TINICASE =   -38.044998 TFINCASE =   -37.748001
 HLOSS=    56.313545 AVTIME =     3.072500
 XHC=   112.007652  XPAN=   1.00712478
 RWX=       16.241806 RWY=       24.585804 SHP=       40.827610


 THIGH= 525.1410 TLOW= 452.1650 Fe=   0.1596794
 FeO=   0.1896921 KCl=   0.1875585 FeS2=   0.1530157
 MgO=   0.2790161 Li=   1.0015823 Al=   0.2666767
 LiF=   0.5975327 LiBr=   0.1842257 LiCl=   0.3774475
 HPHC=   0.1716325 AHC=   0.3989231 ECHC=   0.2093058
 EUT=   0.2663107 XHC=      382.16327
 CPINS=   0.2209410 CPHPAP=      0.1400
 TSTHC=       37.55689 THPHC=       92.87337
```

TECHC= 91.00438 TINSHC= 76.30403
TAHC= 68.93684 THPAPC= 14.41059
T1= 725.314941 T2= 798.291016 TEUTFUS= 0.000000

K= 0.0000987658 TAVSTACK= 488.65298 TAVINS= 226.91100
TIME1= 4.06700 TIME2= 185.50400
TINICASE = -37.748001 TFINCASE = -31.914000
HLOSS= 2.106314 AVTIME = 94.785500
XHC= 382.163269 XPAN= 1.00635517
RWX= 16.209747 RWY= 24.529522 SHP= 40.739269

THIGH= 452.1650 TLOW= 336.8180 Fe= 0.1474725
FeO= 0.1864399 KCl= 0.1815421 FeS2= 0.1506242
MgO= 0.2729953 Li= 1.0091888 Al= 0.2563461
LiF= 0.5087395 LiBr= 0.1608118 LiCl= 0.3247025
HPHC= 0.1628081 AHC= 0.3892416 ECHC= 0.1975553
EUT= 0.2301839 XHC= 694.22089
CPINS= 0.2165095 CPHPAP= 0.1400
TSTHC= 54.82486 THPHC= 139.24934
TECHC= 135.76733 TINSHC= 118.18807
TAHC= 106.31804 THPAPC= 22.77756
T1= 609.968018 T2= 725.314941 TEUTFUS= 115.480637

K= 0.0001273994 TAVSTACK= 394.49149 TAVINS= 181.99875
TIME1= 185.50400 TIME2= 501.54199
TINICASE = -31.914000 TFINCASE = -29.073999
HLOSS= 2.196637 AVTIME = 343.523010
XHC= 694.220886 XPAN= 1.00488472
RWX= 16.148718 RWY= 24.422386 SHP= 40.571106

THIGH= 336.8180 TLOW= 270.9165 Fe= 0.1359819
FeO= 0.1830766 KCl= 0.1759994 FeS2= 0.1477130
MgO= 0.2663206 Li= 1.0199302 Al= 0.2464037
LiF= 0.4720328 LiBr= 0.1524766 LiCl= 0.3057763
HPHC= 0.1544157 AHC= 0.3826784 ECHC= 0.1910823
EUT= 0.2168026 XHC= 319.12726
CPINS= 0.2121134 CPHPAP= 0.1400
TSTHC= 28.88262 THPHC= 75.45673
TECHC= 75.02674 TINSHC= 66.15366
TAHC= 59.71877 THPAPC= 13.01357
T1= 544.066528 T2= 609.968018 TEUTFUS= 0.000000

K= 0.0001184207 TAVSTACK= 303.86725 TAVINS= 137.44437
TIME1= 501.54199 TIME2= 701.84900
TINICASE = -29.073999 TFINCASE = -28.882999
HLOSS= 1.593191 AVTIME = 601.695496
XHC= 319.127258 XPAN= 1.00355816
RWX= 16.093908 RWY= 24.326174 SHP= 40.420082

THIGH= 270.9165 TLOW= 188.5045 Fe= 0.1269573
FeO= 0.1799822 KCl= 0.1718273 FeS2= 0.1444362
MgO= 0.2595669 Li= 1.0337398 Al= 0.2382678
LiF= 0.4557335 LiBr= 0.1498979 LiCl= 0.2998284
HPHC= 0.1476959 AHC= 0.3788430 ECHC= 0.1866207
EUT= 0.2121696 XHC= 388.16168
CPINS= 0.2084532 CPHPAP= 0.1400
TSTHC= 33.72163 THPHC= 90.25482
TECHC= 91.63280 TINSHC= 81.29990
TAHC= 73.93186 THPAPC= 16.27391
T1= 461.654480 T2= 544.066528 TEUTFUS= 0.000000

K= 0.0001232613 TAVSTACK= 229.71051 TAVINS= 100.35001
TIME1= 701.84900 TIME2= 1003.84601
TINICASE = -28.882999 TFINCASE = -29.138000
HLOSS= 1.285316 AVTIME = 852.847534
XHC= 388.161682 XPAN= 1.00253749
RWX= 16.051895 RWY= 24.252434 SHP= 40.304329

THIGH= 188.5045 TLOW= 130.0240 Fe= 0.1188910
FeO= 0.1765838 KCl= 0.1683510 FeS2= 0.1401244
MgO= 0.2514198 Li= 0.9955296 Al= 0.2305391
LiF= 0.4377404 LiBr= 0.1474484 LiCl= 0.2941781
HPHC= 0.1415102 AHC= 0.3659364 ECHC= 0.1813276
EUT= 0.2075284 XHC= 266.60687
CPINS= 0.2049433 CPHPAP= 0.1400
TSTHC= 22.40887 THPHC= 61.36345
TECHC= 63.17935 TINSHC= 56.71988
TAHC= 50.67551 THPAPC= 11.54814
T1= 403.174011 T2= 461.654480 TEUTFUS= 0.000000

K= 0.0001161792 TAVSTACK= 159.26425 TAVINS= 64.77788
TIME1= 1003.84601 TIME2= 1305.91699
TINICASE = -29.138000 TFINCASE = -30.278999

HLOSS=   0.882597 AVTIME = 1154.881470
XHC=   266.606873 XPAN=   1.00162184
RWX=   16.014320 RWY=   24.186497 SHP=   40.200817

THIGH= 130.0240 TLOW= 87.2465 Fe=   0.1136413
FeO=   0.1736458 KCl=   0.1663789 FeS2=   0.1357300
MgO=   0.2436940 Li=   0.9302480 Al=   0.2249846
LiF=   0.4220979 LiBr=   0.1456879 LiCl=   0.2901172
HPHC=   0.1372783 AHC=   0.3498269 ECHC=   0.1763837
EUT=   0.2039336 XHC=   189.53038
CPINS=   0.2024008 CPHPAP=   0.1400
TSTHC=   15.66794 THPHC=   43.54404
TECHC=   44.95465 TINSHC=   40.97495
TAHC=   35.43649 THPAPC=   8.44728
T1= 360.396484 T2=   403.174011 TEUTFUS=   0.000000

K= 0.0001130564 TAVSTACK=   108.63525 TAVINS=   39.00938
TIME1= 1305.91699 TIME2=   1605.91003
TINICASE =   -30.278999 TFINCASE =   -30.954000
HLOSS=   0.631783 AVTIME = 1455.913574
XHC=   189.530380 XPAN=   1.00099623
RWX=   15.988710 RWY=   24.141554 SHP=   40.130264

THIGH= 87.2465 TLOW= 47.7215 Fe=   0.1099526
FeO=   0.1707343 KCl=   0.1653319 FeS2=   0.1307898
MgO=   0.2354385 Li=   0.8857958 Al=   0.2204698
LiF=   0.4065198 LiBr=   0.1442569 LiCl=   0.2868166
HPHC=   0.1340644 AHC=   0.3382553 ECHC=   0.1711615
EUT=   0.2007378 XHC=   170.99275
CPINS=   0.2003085 CPHPAP=   0.1400
TSTHC=   14.00676 THPHC=   39.29129
TECHC=   40.30680 TINSHC=   37.46811
TAHC=   31.65907 THPAPC=   7.80500
T1= 320.871490 T2=   360.396484 TEUTFUS=   0.000000

K= 0.0001077942 TAVSTACK=   67.48400 TAVINS=   17.80475
TIME1= 1605.91003 TIME2=   2004.29297
TINICASE =   -30.954000 TFINCASE =   -32.794998
HLOSS=   0.429217 AVTIME = 1805.101562
XHC=   170.992752 XPAN=   1.00050783
RWX=   15.968754 RWY=   24.106537 SHP=   40.075291

THIGH= 47.7215 TLOW= 11.3135 Fe= 0.1072796
FeO= 0.1673871 KCl= 0.1650679 FeS2= 0.1245042
MgO= 0.2253271 Li= 0.8530105 Al= 0.2163045
LiF= 0.3885316 LiBr= 0.1429368 LiCl= 0.2837714
HPHC= 0.1313842 AHC= 0.3290255 ECHC= 0.1648233
EUT= 0.1974435 XHC= 153.95322
CPINS= 0.1983436 CPHPAP= 0.1400
TSTHC= 12.58850 THPHC= 35.46917
TECHC= 35.75328 TINSHC= 34.17476
TAHC= 28.36664 THPAPC= 7.18949
T1= 284.463501 T2= 320.871490 TEUTFUS= 0.000000

K= 0.0001000072 TAVSTACK= 29.51750 TAVINS= -2.10950
TIME1= 2004.29297 TIME2= 2612.31982
TINICASE = -32.794998 TFINCASE = -34.678001
HLOSS= 0.253201 AVTIME = 2308.306396
XHC= 153.953217 XPAN= 1.00007308
RWX= 15.951015 RWY= 24.075411 SHP= 40.026428

THIGH= 11.3135 TLOW= -6.0765 Fe= 0.1059997
FeO= 0.1644599 KCl= 0.1654710 FeS2= 0.1185982
MgO= 0.2160657 Li= 0.8366989 Al= 0.2133534
LiF= 0.3727469 LiBr= 0.1420014 LiCl= 0.2816139
HPHC= 0.1297250 AHC= 0.3237021 ECHC= 0.1590548
EUT= 0.1948187 XHC= 72.31541
CPINS= 0.1969561 CPHPAP= 0.1400
TSTHC= 5.94107 THPHC= 16.72764
TECHC= 16.47962 TINSHC= 16.20914
TAHC= 13.32991 THPAPC= 3.43401
T1= 267.073486 T2= 284.463501 TEUTFUS= 0.000000

K= 0.0000969349 TAVSTACK= 2.61850 TAVINS= -16.17125
TIME1= 2612.31982 TIME2= 3108.70288
TINICASE = -34.678001 TFINCASE = -35.243999
HLOSS= 0.145685 AVTIME = 2860.511230
XHC= 72.315407 XPAN= 0.99977434
RWX= 15.938841 RWY= 24.054050 SHP= 39.992889

THIGH= -6.0765 TLOW= -18.0760 Fe= 0.1056346
FeO= 0.1625583 KCl= 0.1660124 FeS2= 0.1145812
MgO= 0.2098647 Li= 0.8315525 Al= 0.2117412

LiF= 0.3624693 LiBr= 0.1414904 LiCl= 0.2804353
HPHC= 0.1289490 AHC= 0.3214558 ECHC= 0.1552080
EUT= 0.1932266 XHC= 49.43303
CPINS= 0.1961919 CPHPAP= 0.1400
TSTHC= 4.08535 THPHC= 11.47340
TECHC= 11.09629 TINSHC= 11.14127
TAHC= 9.13410 THPAPC= 2.36954
T1= 255.073990 T2= 267.073486 TEUTFUS= 0.000000

K= 0.0000979373 TAVSTACK= -12.07625 TAVINS= -23.91613
TIME1= 3108.70288 TIME2= 3641.91992
TINICASE = -35.243999 TFINCASE = -36.268002
HLOSS= 0.092707 AVTIME = 3375.311523
XHC= 49.433025 XPAN= 0.99961436
RWX= 15.932324 RWY= 24.042618 SHP= 39.974941

THIGH= -18.0760 TLOW= -19.5700 Fe= 0.1055582
FeO= 0.1616028 KCl= 0.1663485 FeS2= 0.1125214
MgO= 0.2067065 Li= 0.8302168 Al= 0.2110012
LiF= 0.3572999 LiBr= 0.1412558 LiCl= 0.2798942
HPHC= 0.1286283 AHC= 0.3206051 ECHC= 0.1532523
EUT= 0.1924525 XHC= 6.12777
CPINS= 0.1958338 CPHPAP= 0.1400
TSTHC= 0.50828 THPHC= 1.42495
TECHC= 1.36414 TINSHC= 1.38462
TAHC= 1.13424 THPAPC= 0.29502
T1= 253.579987 T2= 255.073990 TEUTFUS= 0.000000

K= 0.0000991679 TAVSTACK= -18.82300 TAVINS= -27.54550
TIME1= 3641.91992 TIME2= 3730.54590
TINICASE = -36.268002 TFINCASE = -36.268002
HLOSS= 0.069142 AVTIME = 3686.232910
XHC= 6.127772 XPAN= 0.99954170
RWX= 15.929368 RWY= 24.037428 SHP= 39.966797

HFUSEC = 17.5326 HFUSA = 7.02 HFUSEUT = 70.2
ECMASS = 5.958 ANODEMASS = 2.368
HPELLETMASS = 7.415 STEELSTACKMASS = 3.223
INSMASS = 9.465 HEAT PAPER MASS =2.821

E-3. GPS9Q (10.67 Atmospheres Operating Pressure) Output File

This is 8478 March 24 2008 18:36 qcork2o in /usr2/users/fkrieger/vk on push.

```
 THIGH= 508.9015 TLOW= 491.7365 Fe=   0.1612032
 FeO=   0.1900847 KCl=   0.1883149 FeS2=   0.1532847
 MgO=   0.2797228 Li=   1.0007927 Al=   0.2679566
 LiF=   0.5975327 LiBr=   0.1842257 LiCl=   0.3774475
 HPHC=   0.1727303 AHC=   0.3997025 ECHC=   0.2096212
 EUT=   0.2663107 XHC=       90.19954
 CPINS=   0.2213916 CPHPAP=      0.1400
 TSTHC=        8.91823 THPHC=       21.98490
 TECHC=       21.43781 TINSHC=       17.98442
 TAHC=       16.24663 THPAPC=        3.38958
 T1=  764.886475 T2=   782.051514  TEUTFUS=     0.000000


 K= 0.0000588844 TAVSTACK=    500.31900  TAVINS=    231.47725
 TIME1=    24.68200 TIME2=     94.57500
 TINICASE =   -39.562000 TFINCASE =   -35.167000
 HLOSS=     1.290538 AVTIME =    59.628498
 XHC=    90.199539  XPAN=   1.00654387
 RWX=       16.217602 RWY=       24.543308 SHP=       40.760910


 THIGH= 491.7365 TLOW= 438.4345 Fe=   0.1565991
 FeO=   0.1889007 KCl=   0.1860286 FeS2=   0.1524762
 MgO=   0.2775945 Li=   1.0031544 Al=   0.2640911
 LiF=   0.5975327 LiBr=   0.1842257 LiCl=   0.3774475
 HPHC=   0.1694141 AHC=   0.3973445 ECHC=   0.2086721
 EUT=   0.2663107 XHC=      276.98074
 CPINS=   0.2198414 CPHPAP=      0.1400
 TSTHC=       26.90253 THPHC=       66.95827
 TECHC=       66.26871 TINSHC=       55.45537
 TAHC=       50.15248 THPAPC=       10.52555
 T1=  711.584473 T2=   764.886475  TEUTFUS=     0.000000


 K= 0.0002542343 TAVSTACK=    465.08551  TAVINS=    215.76651
 TIME1=    94.57500 TIME2=    148.26300
 TINICASE =   -35.167000 TFINCASE =   -31.938000
 HLOSS=     5.159080 AVTIME =   121.418999
 XHC=   276.980743  XPAN=   1.00597835
 RWX=       16.194082 RWY=       24.502018 SHP=       40.696098
```

THIGH= 438.4345 TLOW= 337.8370 Fe= 0.1466527
FeO= 0.1862167 KCl= 0.1811399 FeS2= 0.1504532
MgO= 0.2725751 Li= 1.0097562 Al= 0.2556489
LiF= 0.4969233 LiBr= 0.1576888 LiCl= 0.3176679
HPHC= 0.1622141 AHC= 0.3883601 ECHC= 0.1961604
EUT= 0.2253679 XHC= 618.18628
CPINS= 0.2162228 CPHPAP= 0.1400
TSTHC= 47.54858 THPHC= 121.00045
TECHC= 117.57073 TINSHC= 102.93890
TAHC= 92.51318 THPAPC= 19.86500
T1= 610.986938 T2= 711.584473 TEUTFUS= 115.480637

K= 0.0003269313 TAVSTACK= 388.13574 TAVINS= 179.09312
TIME1= 148.26300 TIME2= 259.76901
TINICASE = -31.938000 TFINCASE = -27.961000
HLOSS= 5.543972 AVTIME = 204.016006
XHC= 618.186279 XPAN= 1.00478888
RWX= 16.144751 RWY= 24.415419 SHP= 40.560169

THIGH= 337.8370 TLOW= 221.8400 Fe= 0.1330357
FeO= 0.1820938 KCl= 0.1746264 FeS2= 0.1467032
MgO= 0.2642072 Li= 1.0241133 Al= 0.2437675
LiF= 0.4668602 LiBr= 0.1516410 LiCl= 0.3038490
HPHC= 0.1522298 AHC= 0.3813842 ECHC= 0.1896823
EUT= 0.2153118 XHC= 556.60706
CPINS= 0.2110404 CPHPAP= 0.1400
TSTHC= 49.73649 THPHC= 130.93549
TECHC= 131.09132 TINSHC= 115.85181
TAHC= 104.75890 THPAPC= 22.90592
T1= 494.989990 T2= 610.986938 TEUTFUS= 0.000000

K= 0.0003208672 TAVSTACK= 279.83850 TAVINS= 126.57050
TIME1= 259.76901 TIME2= 399.90701
TINICASE = -27.961000 TFINCASE = -25.434000
HLOSS= 3.971849 AVTIME = 329.838013
XHC= 556.607056 XPAN= 1.00322115
RWX= 16.080021 RWY= 24.301800 SHP= 40.381821

THIGH= 221.8400 TLOW= 157.7410 Fe= 0.1222990
FeO= 0.1781354 KCl= 0.1697734 FeS2= 0.1421994
MgO= 0.2552484 Li= 1.0280738 Al= 0.2338882
LiF= 0.4459696 LiBr= 0.1485098 LiCl= 0.2966265

HPHC= 0.1441566 AHC= 0.3744109 ECHC= 0.1838029
EUT= 0.2095809 XHC= 296.83206
CPINS= 0.2066680 CPHPAP= 0.1400
TSTHC= 25.26589 THPHC= 68.51676
TECHC= 70.19468 TINSHC= 62.69244
TAHC= 56.83050 THPAPC= 12.65763
T1= 430.890991 T2= 494.989990 TEUTFUS= 0.000000

K= 0.0003405843 TAVSTACK= 189.79050 TAVINS= 82.25750
TIME1= 399.90701 TIME2= 500.60101
TINICASE = -25.434000 TFINCASE = -25.117001
HLOSS= 2.947862 AVTIME = 450.254028
XHC= 296.832062 XPAN= 1.00201213
RWX= 16.030321 RWY= 24.214577 SHP= 40.244896

THIGH= 157.7410 TLOW= 109.5980 Fe= 0.1161593
FeO= 0.1751689 KCl= 0.1672793 FeS2= 0.1380868
MgO= 0.2477796 Li= 0.9603786 Al= 0.2277311
LiF= 0.4302174 LiBr= 0.1465584 LiCl= 0.2921252
HPHC= 0.1393405 AHC= 0.3574094 ECHC= 0.1789901
EUT= 0.2057479 XHC= 216.29877
CPINS= 0.2039133 CPHPAP= 0.1400
TSTHC= 18.02385 THPHC= 49.74182
TECHC= 51.34079 TINSHC= 46.45895
TAHC= 40.74561 THPAPC= 9.50680
T1= 382.747986 T2= 430.890991 TEUTFUS= 0.000000

K= 0.0003411599 TAVSTACK= 133.66949 TAVINS= 54.33875
TIME1= 500.60101 TIME2= 600.09100
TINICASE = -25.117001 TFINCASE = -24.867001
HLOSS= 2.174076 AVTIME = 550.346008
XHC= 216.298767 XPAN= 1.00130224
RWX= 16.001230 RWY= 24.163527 SHP= 40.164757

THIGH= 109.5980 TLOW= 55.2255 Fe= 0.1112362
FeO= 0.1718398 KCl= 0.1656594 FeS2= 0.1327108
MgO= 0.2386193 Li= 0.9013071 Al= 0.2221076
LiF= 0.4124406 LiBr= 0.1447760 LiCl= 0.2880139
HPHC= 0.1352090 AHC= 0.3423450 ECHC= 0.1731693
EUT= 0.2019229 XHC= 237.25801
CPINS= 0.2013790 CPHPAP= 0.1400
TSTHC= 19.49332 THPHC= 54.51248

TECHC= 56.09842 TINSHC= 51.81840
TAHC= 44.07832 THPAPC= 10.73694
T1= 328.375488 T2= 382.747986 TEUTFUS= 0.000000

K= 0.0003330867 TAVSTACK= 82.41175 TAVINS= 28.65363
TIME1= 600.09100 TIME2= 765.32501
TINICASE = -24.867001 TFINCASE = -25.341999
HLOSS= 1.435891 AVTIME = 682.708008
XHC= 237.258011 XPAN= 1.00068295
RWX= 15.975907 RWY= 24.119083 SHP= 40.094990

THIGH= 55.2255 TLOW= 6.5055 Fe= 0.1073913
FeO= 0.1674908 KCl= 0.1650935 FeS2= 0.1246876
MgO= 0.2256287 Li= 0.8543639 Al= 0.2164524
LiF= 0.3890869 LiBr= 0.1429836 LiCl= 0.2838795
HPHC= 0.1314859 AHC= 0.3293865 ECHC= 0.1650134
EUT= 0.1975525 XHC= 206.16722
CPINS= 0.1987833 CPHPAP= 0.1400
TSTHC= 16.86308 THPHC= 47.50045
TECHC= 47.89906 TINSHC= 45.83295
TAHC= 38.00098 THPAPC= 9.62074
T1= 279.655487 T2= 328.375488 TEUTFUS= 0.000000

K= 0.0003152888 TAVSTACK= 30.86550 TAVINS= 2.34725
TIME1= 765.32501 TIME2= 1051.73804
TINICASE = -25.341999 TFINCASE = -27.000000
HLOSS= 0.719825 AVTIME = 908.531494
XHC= 206.167221 XPAN= 1.00008833
RWX= 15.951639 RWY= 24.076500 SHP= 40.028137

THIGH= 6.5055 TLOW= -11.4360 Fe= 0.1058474
FeO= 0.1638255 KCl= 0.1656333 FeS2= 0.1172700
MgO= 0.2140092 Li= 0.8346258 Al= 0.2127957
LiF= 0.3693201 LiBr= 0.1418246 LiCl= 0.2812062
HPHC= 0.1294464 AHC= 0.3228735 ECHC= 0.1577781
EUT= 0.1942802 XHC= 74.36263
CPINS= 0.1970539 CPHPAP= 0.1400
TSTHC= 6.12067 THPHC= 17.22105
TECHC= 16.86576 TINSHC= 16.73148
TAHC= 13.71743 THPAPC= 3.54291
T1= 261.713989 T2= 279.655487 TEUTFUS= 0.000000

K= 0.0003194099 TAVSTACK= -2.46525 TAVINS= -15.18038
TIME1= 1051.73804 TIME2= 1280.68799
TINICASE = -27.000000 TFINCASE = -28.791000
HLOSS= 0.324799 AVTIME = 1166.213013
XHC= 74.362625 XPAN= 0.99971879
RWX= 15.936578 RWY= 24.050077 SHP= 39.986656

THIGH= -11.4360 TLOW= -18.6170 Fe= 0.1055913
FeO= 0.1621493 KCl= 0.1661499 FeS2= 0.1137037
MgO= 0.2085171 Li= 0.8308572 Al= 0.2114175
LiF= 0.3602572 LiBr= 0.1413878 LiCl= 0.2801986
HPHC= 0.1288049 AHC= 0.3210642 ECHC= 0.1543732
EUT= 0.1928927 XHC= 29.52267
CPINS= 0.1963496 CPHPAP= 0.1400
TSTHC= 2.44384 THPHC= 6.85849
TECHC= 6.60476 TINSHC= 6.67276
TAHC= 5.45957 THPAPC= 1.41803
T1= 254.532990 T2= 261.713989 TEUTFUS= 0.000000

K= 0.0003102466 TAVSTACK= -15.02650 TAVINS= -22.31750
TIME1= 1280.68799 TIME2= 1443.94897
TINICASE = -28.791000 TFINCASE = -30.426001
HLOSS= 0.180831 AVTIME = 1362.318481
XHC= 29.522673 XPAN= 0.99958253
RWX= 15.931029 RWY= 24.040342 SHP= 39.971371

HFUSEC = 17.5326 HFUSA = 7.02 HFUSEUT = 70.2
ECMASS = 5.958 ANODEMASS = 2.368
HPELLETMASS = 7.415 STEELSTACKMASS = 3.223
INSMASS = 9.465 HEAT PAPER MASS =2.821

Appendix F. Fortran Programs for Insulation Package Thermal Conductivity Values from Copper–Heat Pellet Stack Cooling Curves

Fortran programs used to determine the global thermal insulation package thermal conductivity values from the cooling curves of the copper–heat pellet stack experiment are shown in appendices F-1 and F-2. A heat balance calculation for a single simulated thermal cell in the copper–heat paper stack is shown in appendix F-3. The component masses used were measured while building the copper–heat pellet stack. Heat contents of other thermal battery materials are again included to facilitate rewriting the source file program for future applications.

F-1. Source File

This is 11223 March 24 2008 17:49 kcu3.for in /usr2/users/fkrieger/vk on push.

```
C  1= Fe      6= LiF(s)      11= LiCl(l)      16= Al(l)
C  2= FeO     7= LiF(l)      12= Cu           17= Heat Pellet
C  3= KCl(s)  8= LiBr(s)     13= Li(s)        18= Anode
C  4= FeS2    9= LiBr(l)     14= Li(l)        19= Elec-Cathode
C  5= MgO     10=LiCl(s)     15= Al(s)        20= Eutectic

C     PR1= Weight fraction Fe, FeO, KCl in burned heat pellet.
C     PR2= Weight fraction LiF, LiBr, LiCl, Li, Al, in anode.
C     PR3= Weight fraction Fe, FeS2, MgO, LiF, LiBr, LiCl, in
C     electrolyte/cathode.
C     GMW= Gram molecular weights of first 16 substances.
C
C     703.15 K = 430 C = Melting point of LiF-LiBr-LiCl eutectic.
C     453.7  K = 180.55 C = Melting point of Lithium.
C     932 K = 658.85 C = Melting point of Aluminum.
C     70.20 cal/g  = Heat of fusion of LiF-LiBr-LiCl eutectic.
C     17.5326 cal/g  = Heat of fusion of LiF-LiBr-KBr eutectic in
C         electrolyte-cathode (70.20*(.0238872+.170860+.0550045)
C         = 17.5326).
C     7.02 cal/g  = Heat of fusion of LiF-LiBr-LiCl eutectic in
C     anode (70.2*(.00956438+.0684120+.0220237)=7.02) (Li(Al)).
C     The experimental cathode uses 45/55 E/B and anode uses only E.
C     The separator uses 53/47 E/B. The E/C composition was
C     calculated using 53/47 E/B for both separators and cathodes.
C     All heat capacities calculated as sum of component
C     heat capacities.
C     Liquid lithium heat capacity used above 453.7 K.
C     Liquid aluminum heat capacity used above 932 K.
C     Heat of fusion of lithium 715/6.94 = 103.026 c/g is ignored.
C     Heat of fusion of aluminum 2570/26.98 = 95.2557 c/g is ignored.
```

```
C     T (K) = T (C) + 273.15


      DIMENSION PR1(16),PR2(16),PR3(16),GMW(16),DELH(21)

      DATA
     1 PR1/0.595687,0.318222,0.0861032,0.,0.,0.,0.,0.,0.,0.,0.,0.,0.,
     1 0.,0.,0./,
     2 PR2/0.,0.,0.,0.,0.,.00956438,0.,.0684120,0.,.0220237,0.,
     3     0.,0.18,0.,0.72,0./,
     4 PR3/0.0132193,0.,0.,0.515552,0.221478,.0238872,0.,.170860,0.,
     5    .0550045,0.,0.,0.,0.,0.,0./,
     6 GMW/55.85,68.89,74.56,119.98,40.32,25.94,25.94,86.85,86.85,
     7 42.39,42.39,63.54,6.94,6.94,26.98,26.98/


      OPEN(UNIT=5,NAME='/usr2/users/fkrieger/vk/kcu3i',TYPE='OLD')
      OPEN(UNIT=6,NAME='/usr2/users/fkrieger/vk/qfile',TYPE='NEW')
      READ(5,111) TI1,TT1,TCE1,TB1,TC1
 8    READ(5,111,END=219) TI2,TT2,TCE2,TB2,TC2
 111  FORMAT(F12.7,F14.7,F14.7,F15.7,F15.7)
      THIGH=(TT1+2*TCE1+TB1)/4.
      TLOW=(TT2+2*TCE2+TB2)/4.
      TCASE=0.5*(TC1+TC2)
      TIME= TI2-TI1
      TM=(THIGH+TLOW)/2.
      TIN=(TM+TCASE)/2.
      T1=TLOW+273.15
      T2=THIGH+273.15
      DO  I=1,5
      IF((T2-T1).EQ.0.) GO TO 19
        DELH(I)=ENTG(T1,T2,I)/GMW(I)/(T2-T1)
      END DO

      DELH(12) = ENTG(T1,T2,12)/GMW(12)/(T2-T1)

          IF(T2.LT.703.15) THEN
            DELH(6) = ENTG(T1,T2,6)/GMW(6)/(T2-T1)
            DELH(8) = ENTG(T1,T2,8)/GMW(8)/(T2-T1)
            DELH(10)= ENTG(T1,T2,10)/GMW(10)/(T2-T1)
          ELSE IF(T1.GT.703.15) THEN
            DELH(6) = ENTG(T1,T2,7)/GMW(7)/(T2-T1)
            DELH(8) = ENTG(T1,T2,9)/GMW(9)/(T2-T1)
            DELH(10)= ENTG(T1,T2,11)/GMW(11)/(T2-T1)
          ELSE
            DELH(6) = ENTG(T1,703.15,6)/GMW(6)/(T2-T1)
```

```
     1            + ENTG(703.15,T2,7)/GMW(7)/(T2-T1)
          DELH(8) = ENTG(T1,703.15,8)/GMW(8)/(T2-T1)
     1            + ENTG(703.15,T2,9)/GMW(9)/(T2-T1)
          DELH(10)= ENTG(T1,703.15,10)/GMW(10)/(T2-T1)
     1            + ENTG(703.15,T2,11)/GMW(11)/(T2-T1)
        END IF
        IF(T2.LT.453.7) THEN
          DELH(13)= ENTG(T1,T2,13)/GMW(13)/(T2-T1)
        ELSE IF(T1.GT.453.7) THEN
          DELH(13)= ENTG(T1,T2,14)/GMW(14)/(T2-T1)
        ELSE
          DELH(13)= ENTG(T1,453.7,13)/GMW(13)/(T2-T1)
     1            + ENTG(453.7,T2,14)/GMW(14)/(T2-T1)
        END IF
        IF(T2.LT.932.0) THEN
          DELH(15)= ENTG(T1,T2,15)/GMW(15)/(T2-T1)
        ELSE IF(T1.GT.932.0) THEN
          DELH(15)= ENTG(T1,T2,16)/GMW(16)/(T2-T1)
        ELSE
          DELH(15)= ENTG(T1,932.0,15)/GMW(15)/(T2-T1)
     1            + ENTG(932.0,T2,16)/GMW(16)/(T2-T1)
        END IF

      DELH(17)=0.0
      DELH(18)=0.0
      DELH(19)=0.0

      DO J=1,16
        DELH(17)=DELH(J)*PR1(J)+DELH(17)
        DELH(18)=DELH(J)*PR2(J)+DELH(18)
        DELH(19)=DELH(J)*PR3(J)+DELH(19)
      END DO

      DELH(20)=.0956438*DELH(6)+.684120*DELH(8)+.220237*DELH(10)

      CPHPAP = 0.14
      CPINS =.1716+.00009867*(TIN+273.15)
C     Expansion of the battery stack components with temperature.
      XPAN=1.+.000016*(TM-22.)
      FL1=.8145*2.54
      FL2=1.23825*2.54
      D1=0.75*2.54
      D2=1.2455*2.54
      PI=3.1415927
      RWX=PI*((D1*XPAN)**2/(FL2-FL1*XPAN)+1.08*D1*XPAN)
      RWY=PI*2.*FL1*XPAN/ALOG(D2/D1/XPAN)
```

```
      SHP=RWX+RWY

      XHC   = (T2-T1)*((1.194*DELH(1)+8.853*DELH(17)
     1+30.644*DELH(12))+(CPHPAP*3.242+CPINS*10.474
     1+0.277*DELH(1))*.5)
C     IF(THIGH.GT.430.01.AND.TLOW.LT.429.99) THEN
C     TEUTFUS=7.02*1.570+17.5326*5.958
C     XHC=XHC+TEUTFUS
C     ELSE
C     TEUTFUS=0.0
C     END IF
      COND= XHC/(SHP*TIME*(TM-TCASE))
      AVTI= (TI1+TI2)/2.
      HLOSS= COND*SHP*(TM-TCASE)

      TSTHC = 1.194*(T2-T1)*DELH(1)
      THPHC = 8.853*(T2-T1)*DELH(17)
      TCUHC = 30.644*(T2-T1)*DELH(12)
C     TECHC = 5.958*(T2-T1)*DELH(19)
      THPAPC= 3.242*(T2-T1)*.5*CPHPAP
      TINSHC= 10.474*(T2-T1)*.5*CPINS
      TCUHC = 30.644*(T2-T1)*DELH(12)


      WRITE(6,220) THIGH,TLOW,DELH(1)
      WRITE(6,221) DELH(2),DELH(3),DELH(4)
      WRITE(6,222) DELH(5),DELH(13),DELH(15)
      WRITE(6,223) DELH(6),DELH(8),DELH(10)
      WRITE(6,224) DELH(17),DELH(12),DELH(19)
      WRITE(6,225) DELH(20),DELH(12),XHC
      WRITE(6,231) CPINS,CPHPAP
      WRITE(6,250) TSTHC,THPHC,TCUHC
      WRITE(6,251) TECHC,TINSHC
      WRITE(6,252) TAHC,THPAPC
      WRITE(6,235) T1,T2,TEUTFUS
      WRITE(6,232) COND,TM,TIN
      WRITE(6,233) TI1,TI2,TIME
      WRITE(6,237) TC1,TC2,TCASE
      WRITE(6,236) HLOSS,AVTI
      WRITE(6,242) XHC,XPAN
      WRITE(6,243) RWX,RWY,SHP


 19   TI1=TI2
      TT1=TT2
      TCE1=TCE2
```

```
      TB1=TB2
      TC1=TC2
      GO TO 8
 219  WRITE(6,226)
      WRITE(6,227)
      WRITE(6,228)
      WRITE(6,229)
 220  FORMAT(' THIGH=' ,F9.4,' TLOW=',F9.4,' Fe=', F12.7)
 221  FORMAT(' FeO=' ,F12.7,' KCl=',F12.7,' FeS2=', F12.7)
 222  FORMAT(' MgO=' ,F12.7,' Li=' ,F12.7,' Al=', F12.7)
 223  FORMAT(' LiF=', F12.7,' LiBr=',F12.7,' LiCl=', F12.7)
 224  FORMAT(' HPHC=', F12.7,' CUHC=',F12.7,' ECHC=', F12.7)
 225  FORMAT(' EUT=' ,F12.7, ' Cu=',F12.7' XHC=',F15.5)
 226  FORMAT(' HFUSEC = 17.5326  HFUSA = 7.02  HFUSEUT = 70.2')
 227  FORMAT(' ECMASS = 0.000  ANODEMASS = 0.000')
 228  FORMAT(' HPELLETMASS = 8.853  STEELSTACKMASS = 1.194')
 229  FORMAT(' INSMASS = 10.474 HEAT PAPER MASS =3.242')
 231  FORMAT(' CPINS=' ,F12.7, ' CPHPAP=' , F12.4)
 232  FORMAT(' K=' ,F13.10,  ' TAVSTACK= ' ,F12.5, '  TAVINS= ' ,F12.5)
 233  FORMAT(' TIME1=' ,F12.5, ' TIME2= ' ,F12.5, ' INTTIME= ' ,F12.5)
 235  FORMAT(' T1=' ,F12.6,  ' T2= ' ,F12.6, '  TEUTFUS= ' ,F12.6//)
 236  FORMAT(' HLOSS= ' ,F12.6, ' AVTIME = ' , F12.6)
 237  FORMAT(' TICASE= ' ,F10.4,' TFCASE= ' ,F10.4, ' TCASE= ' ,F10.4)
 242  FORMAT(' XHC= ',F12.6,'  XPAN= ',F12.8)
 243  FORMAT(' RWX= ',F15.6,' RWY= ',F15.6,' SHP= ',F15.6//)

 250  FORMAT(' TSTHC=' ,F15.5, ' THPHC=',F15.5, ' TCUHC=',F15.5)
 251  FORMAT(' TECHC=' ,F15.5, ' TINSHC=',F15.5)
 252  FORMAT(' TAHC=' ,F15.5,  ' THPAPC=',F15.5)

 999  CONTINUE
      END

      FUNCTION ENTG(T1,T2,J)
C     This function calculates the molar heat content between T1 and T2.
C     TR1, TR2, TR3 are molar heat capacity coefficients of the first
C     16 substances.

      DIMENSION TR1(16),TR2(16),TR3(16)
      DATA
     2 TR1/ 3.04, 11.66, 9.89, 17.88, 10.18, 10.41, 15.50, 11.50,
     3     16.00, 11.00, 16.00, 5.41, 1.64, 6.78, 4.94, 7.00/,
     4 TR2/ 0.00758, 0.002, 0.0052, 0.00132, .00174, 0.00390, 0.,
     5     0.00302, 0., .0034, 0., .00150, .0111, 0., .00296, 0./,
     6 TR3/ 60000., -67000., 77000.,-305000.,-148000.,-138000., 0.,
     7     0., 0., 0., 0.,0., 84000., 99000., 0., 0./
```

```
ENTG=(T2-T1)*TR1(J)+.5*(T2*T2-T1*T1)*TR2(J)-(1./T2-1./T1)*TR3(J)
RETURN
END
```

F-2. Output File

These are thermal conductivity values calculated from the experimental points shown in figure 7 of the main report using the source program shown in appendix F-1.

This is 17269 March 24, 2008 17:49 kcu3o in /usr2/users/fkrieger/vk on push.

```
THIGH= 503.4048 TLOW= 471.4673 Fe=   0.1595165
 FeO=   0.1896545 KCl=   0.1874759 FeS2=   0.1529964
 MgO=   0.2789551 Li=   1.0016153 Al=   0.2665431
 LiF=   0.5975327 LiBr=   0.1842257 LiCl=   0.3774475
 HPHC=   0.1715164 CUHC=   0.1030985 ECHC=   0.2092802
 EUT=   0.2663107 Cu=   0.1030985 XHC=      200.35823
 CPINS=   0.2207689 CPHPAP=      0.1400
 TSTHC=        6.08290 THPHC=       48.49502 TCUHC=      100.90174
 TECHC=        0.00000 TINSHC=       36.92507
 TAHC=        0.00000 THPAPC=        7.24790
 T1=  744.617249 T2=   776.554749  TEUTFUS=     0.000000


 K= 0.0004513523 TAVSTACK=    487.43600  TAVINS=    225.16626
 TIME1=     1.04800 TIME2=     20.44900 INTTIME=     19.40100
 TICASE=   -37.2450 TFCASE=   -36.9620 TCASE=   -37.1035
 HLOSS=    10.327211 AVTIME =    10.748501
 XHC=   200.358231  XPAN=   1.00744700
 RWX=       17.418571 RWY=       26.201784 SHP=       43.620354


 THIGH= 471.4673 TLOW= 460.3932 Fe=   0.1567072
 FeO=   0.1889316 KCl=   0.1860810 FeS2=   0.1525020
 MgO=   0.2776549 Li=   1.0030620 Al=   0.2641840
 LiF=   0.5975327 LiBr=   0.1842257 LiCl=   0.3774475
 HPHC=   0.1694928 CUHC=   0.1025909 ECHC=   0.2087002
 EUT=   0.2663107 Cu=   0.1025909 XHC=       69.00060
 CPINS=   0.2197401 CPHPAP=      0.1400
 TSTHC=        2.07204 THPHC=       16.61681 TCUHC=       34.81449
 TECHC=        0.00000 TINSHC=       12.74377
 TAHC=        0.00000 THPAPC=        2.51314
 T1=  733.543213 T2=   744.617249  TEUTFUS=     0.000000


 K= 0.0001043733 TAVSTACK=    465.93024  TAVINS=    214.74011
```

TIME1=   20.44900 TIME2=   50.64700 INTTIME=   30.19800
TICASE=   -36.9620 TFCASE=   -35.9380 TCASE=   -36.4500
HLOSS=   2.284940 AVTIME =   35.548000
XHC=   69.000603 XPAN=   1.00710285
RWX=   17.401587 RWY=   26.174942 SHP=   43.576530

THIGH= 460.3932 TLOW= 440.7605 Fe=   0.1547076
FeO=   0.1884093 KCl=   0.1850914 FeS2=   0.1521329
MgO=   0.2767031 Li=   1.0041853 Al=   0.2624993
LiF=   0.5975327 LiBr=   0.1842257 LiCl=   0.3774475
HPHC=   0.1680502 CUHC=   0.1022284 ECHC=   0.2082727
EUT=   0.2663107 Cu=   0.1022284 XHC=   121.73671
CPINS=   0.2190551 CPHPAP=   0.1400
TSTHC=   3.62657 THPHC=   29.20851 TCUHC=   61.50305
TECHC=   0.00000 TINSHC=   22.52246
TAHC=   0.00000 THPAPC=   4.45544
T1= 713.910522 T2=   733.543213 TEUTFUS=   0.000000

K= 0.0001153728 TAVSTACK=   450.57687 TAVINS=   207.79768
TIME1=   50.64700 TIME2=   100.55101 INTTIME=   49.90401
TICASE=   -35.9380 TFCASE=   -34.0250 TCASE=   -34.9815
HLOSS=   2.439417 AVTIME =   75.599007
XHC=   121.736710 XPAN=   1.00685728
RWX=   17.389479 RWY=   26.155804 SHP=   43.545280

THIGH= 440.7605 TLOW= 399.6020 Fe=   0.1507677
FeO=   0.1873590 KCl=   0.1831497 FeS2=   0.1513599
MgO=   0.2747581 Li=   1.0066466 Al=   0.2591646
LiF=   0.5206953 LiBr=   0.1636260 LiCl=   0.3310856
HPHC=   0.1652019 CUHC=   0.1015108 ECHC=   0.1994861
EUT=   0.2346584 Cu=   0.1015108 XHC=   252.75027
CPINS=   0.2176482 CPHPAP=   0.1400
TSTHC=   7.40923 THPHC=   60.19573 TCUHC=   128.03185
TECHC=   0.00000 TINSHC=   46.91351
TAHC=   0.00000 THPAPC=   9.34053
T1= 672.751953 T2=   713.910522 TEUTFUS=   0.000000

K= 0.0001288362 TAVSTACK=   420.18124 TAVINS=   193.53888
TIME1=   100.55101 TIME2=   200.08202 INTTIME=   99.53101
TICASE=   -34.0250 TFCASE=   -32.1820 TCASE=   -33.1035
HLOSS=   2.539412 AVTIME =   150.316513
XHC=   252.750275 XPAN=   1.00637090

RWX= 17.365536 RWY= 26.117949 SHP= 43.483482

THIGH= 399.6020 TLOW= 360.0955 Fe= 0.1455787
FeO= 0.1859301 KCl= 0.1806107 FeS2= 0.1502419
MgO= 0.2720440 Li= 1.0104302 Al= 0.2547397
LiF= 0.4869993 LiBr= 0.1551187 LiCl= 0.3118706
HPHC= 0.1614376 CUHC= 0.1005587 ECHC= 0.1949246
EUT= 0.2213837 Cu= 0.1005587 XHC= 239.46815
CPINS= 0.2157422 CPHPAP= 0.1400
TSTHC= 6.86705 THPHC= 56.46291 TCUHC= 121.73997
TECHC= 0.00000 TINSHC= 44.63605
TAHC= 0.00000 THPAPC= 8.96560
T1= 633.245483 T2= 672.751953 TEUTFUS= 0.000000

K= 0.0001274655 TAVSTACK= 379.84875 TAVINS= 174.22163
TIME1= 200.08202 TIME2= 305.33600 INTTIME= 105.25398
TICASE= -32.1820 TFCASE= -30.6290 TCASE= -31.4055
HLOSS= 2.275146 AVTIME = 252.709015
XHC= 239.468155 XPAN= 1.00572562
RWX= 17.333838 RWY= 26.067822 SHP= 43.401657

THIGH= 360.0955 TLOW= 326.8737 Fe= 0.1409490
FeO= 0.1845977 KCl= 0.1783684 FeS2= 0.1491186
MgO= 0.2694304 Li= 1.0144888 Al= 0.2507501
LiF= 0.4800185 LiBr= 0.1538542 LiCl= 0.3089539
HPHC= 0.1580626 CUHC= 0.0997002 ECHC= 0.1931622
EUT= 0.2192086 Cu= 0.0997002 XHC= 198.99702
CPINS= 0.2139904 CPHPAP= 0.1400
TSTHC= 5.59099 THPHC= 46.48812 TCUHC= 101.49951
TECHC= 0.00000 TINSHC= 37.23053
TAHC= 0.00000 THPAPC= 7.53934
T1= 600.023743 T2= 633.245483 TEUTFUS= 0.000000

K= 0.0001294269 TAVSTACK= 343.48462 TAVINS= 156.46780
TIME1= 305.33600 TIME2= 400.20898 INTTIME= 94.87299
TICASE= -30.6290 TFCASE= -30.4690 TCASE= -30.5490
HLOSS= 2.097510 AVTIME = 352.772491
XHC= 198.997025 XPAN= 1.00514376
RWX= 17.305323 RWY= 26.022709 SHP= 43.328033

THIGH= 326.8737 TLOW= 294.9710 Fe= 0.1368537

FeO=   0.1833590 KCl=   0.1764091 FeS2=   0.1479934
MgO=   0.2669178 Li=   1.0187925 Al=   0.2471777
LiF=   0.4735180 LiBr=   0.1527219 LiCl=   0.3063422
HPHC=   0.1550602 CUHC=   0.0989315 ECHC=   0.1914791
EUT=   0.2172371 Cu=   0.0989315 XHC=   189.05797
CPINS=   0.2124049 CPHPAP=   0.1400
TSTHC=   5.21302 THPHC=   43.79447 TCUHC=   96.71826
TECHC=   0.00000 TINSHC=   35.48751
TAHC=   0.00000 THPAPC=   7.24002
T1= 568.120972 T2=   600.023743 TEUTFUS=   0.000000

K= 0.0001275930 TAVSTACK=   310.92236 TAVINS=   140.39943
TIME1=   400.20898 TIME2=   500.63501 INTTIME=   100.42603
TICASE=   -30.4690 TFCASE=   -29.7780 TCASE=   -30.1235
HLOSS=   1.882560 AVTIME =   450.421997
XHC=   189.057968 XPAN=   1.00462282
RWX=   17.279848 RWY=   25.982395 SHP=   43.262245

THIGH= 294.9710 TLOW= 266.5440 Fe=   0.1331120
FeO=   0.1821643 KCl=   0.1746439 FeS2=   0.1468279
MgO=   0.2644123 Li=   1.0234703 Al=   0.2438683
LiF=   0.4672381 LiBr=   0.1516730 LiCl=   0.3039227
HPHC=   0.1522992 CUHC=   0.0982194 ECHC=   0.1898116
EUT=   0.2153860 Cu=   0.0982194 XHC=   166.78413
CPINS=   0.2109321 CPHPAP=   0.1400
TSTHC=   4.51807 THPHC=   38.32825 TCUHC=   85.56059
TECHC=   0.00000 TINSHC=   31.40193
TAHC=   0.00000 THPAPC=   6.45122
T1= 539.693970 T2=   568.120972 TEUTFUS=   0.000000

K= 0.0001236059 TAVSTACK=   280.75751 TAVINS=   125.47301
TIME1=   500.63501 TIME2=   601.20300 INTTIME=   100.56799
TICASE=   -29.7780 TFCASE=   -29.8450 TCASE=   -29.8115
HLOSS=   1.658422 AVTIME =   550.919006
XHC=   166.784134 XPAN=   1.00414014
RWX=   17.256287 RWY=   25.945103 SHP=   43.201389

THIGH= 266.5440 TLOW= 240.7975 Fe=   0.1298052
FeO=   0.1810436 KCl=   0.1731099 FeS2=   0.1456560
MgO=   0.2619815 Li=   1.0283746 Al=   0.2408966
LiF=   0.4613369 LiBr=   0.1507311 LiCl=   0.3017502
HPHC=   0.1498406 CUHC=   0.0975800 ECHC=   0.1882039

EUT= 0.2136988 Cu= 0.0975800 XHC= 149.69936
CPINS= 0.2096014 CPHPAP= 0.1400
TSTHC= 3.99038 THPHC= 34.15368 TCUHC= 76.98811
TECHC= 0.00000 TINSHC= 28.26143
TAHC= 0.00000 THPAPC= 5.84290
T1= 513.947510 T2= 539.693970 TEUTFUS= 0.000000

K= 0.0001233040 TAVSTACK= 253.67075 TAVINS= 111.98587
TIME1= 601.20300 TIME2= 700.50098 INTTIME= 99.29797
TICASE= -29.8450 TFCASE= -29.5530 TCASE= -29.6990
HLOSS= 1.507577 AVTIME = 650.851990
XHC= 149.699356 XPAN= 1.00370669
RWX= 17.235167 RWY= 25.911667 SHP= 43.146835

THIGH= 240.7975 TLOW= 217.1273 Fe= 0.1268421
FeO= 0.1799728 KCl= 0.1717619 FeS2= 0.1444604
MgO= 0.2595813 Li= 1.0335581 Al= 0.2381858
LiF= 0.4556888 LiBr= 0.1498719 LiCl= 0.2997684
HPHC= 0.1476187 CUHC= 0.0969967 ECHC= 0.1866260
EUT= 0.2121343 Cu= 0.0969967 XHC= 136.49545
CPINS= 0.2083918 CPHPAP= 0.1400
TSTHC= 3.58485 THPHC= 30.93391 TCUHC= 70.35666
TECHC= 0.00000 TINSHC= 25.83249
TAHC= 0.00000 THPAPC= 5.37173
T1= 490.277252 T2= 513.947510 TEUTFUS= 0.000000

K= 0.0001222622 TAVSTACK= 228.96237 TAVINS= 99.72743
TIME1= 700.50098 TIME2= 800.72400 INTTIME= 100.22302
TICASE= -29.5530 TFCASE= -29.4620 TCASE= -29.5075
HLOSS= 1.361917 AVTIME = 750.612488
XHC= 136.495453 XPAN= 1.00331140
RWX= 17.215937 RWY= 25.881214 SHP= 43.097153

THIGH= 217.1273 TLOW= 176.1163 Fe= 0.1230666
FeO= 0.1784782 KCl= 0.1700964 FeS2= 0.1426521
MgO= 0.2560884 Li= 1.0385599 Al= 0.2346376
LiF= 0.4477869 LiBr= 0.1487474 LiCl= 0.2971744
HPHC= 0.1447507 CUHC= 0.0962332 ECHC= 0.1843467
EUT= 0.2100379 Cu= 0.0962332 XHC= 233.93996
CPINS= 0.2067875 CPHPAP= 0.1400
TSTHC= 6.02622 THPHC= 52.55471 TCUHC= 120.94026
TECHC= 0.00000 TINSHC= 44.41272

TAHC= 0.00000 THPAPC= 9.30704
T1= 449.266235 T2= 490.277252 TEUTFUS= 0.000000

K= 0.0001174342 TAVSTACK= 196.62177 TAVINS= 83.46788
TIME1= 800.72400 TIME2= 1005.28204 INTTIME= 204.55804
TICASE= -29.4620 TFCASE= -29.9100 TCASE= -29.6860
HLOSS= 1.143636 AVTIME = 903.003052
XHC= 233.939957 XPAN= 1.00279391
RWX= 17.190805 RWY= 25.841412 SHP= 43.032219

THIGH= 176.1163 TLOW= 143.5735 Fe= 0.1189361
FeO= 0.1766312 KCl= 0.1683591 FeS2= 0.1402105
MgO= 0.2515599 Li= 0.9935035 Al= 0.2306029
LiF= 0.4379945 LiBr= 0.1474686 LiCl= 0.2942246
HPHC= 0.1415529 CUHC= 0.0953650 ECHC= 0.1814156
EUT= 0.2075768 Cu= 0.0953650 XHC= 183.35417
CPINS= 0.2049466 CPHPAP= 0.1400
TSTHC= 4.62138 THPHC= 40.78149 TCUHC= 95.10172
TECHC= 0.00000 TINSHC= 34.92828
TAHC= 0.00000 THPAPC= 7.38525
T1= 416.723511 T2= 449.266235 TEUTFUS= 0.000000

K= 0.0001145978 TAVSTACK= 159.84488 TAVINS= 64.81094
TIME1= 1005.28204 TIME2= 1201.23706 INTTIME= 195.95502
TICASE= -29.9100 TFCASE= -30.5360 TCASE= -30.2230
HLOSS= 0.935695 AVTIME = 1103.259521
XHC= 183.354172 XPAN= 1.00220549
RWX= 17.162287 RWY= 25.796228 SHP= 42.958515

THIGH= 143.5735 TLOW= 103.0078 Fe= 0.1150902
FeO= 0.1745603 KCl= 0.1668818 FeS2= 0.1371693
MgO= 0.2461719 Li= 0.9476027 Al= 0.2265924
LiF= 0.4269759 LiBr= 0.1461975 LiCl= 0.2912927
HPHC= 0.1384757 CUHC= 0.0945021 ECHC= 0.1779619
EUT= 0.2050076 Cu= 0.0945021 XHC= 225.78186
CPINS= 0.2031085 CPHPAP= 0.1400
TSTHC= 5.57445 THPHC= 49.73059 TCUHC= 117.47525
TECHC= 0.00000 TINSHC= 43.14896
TAHC= 0.00000 THPAPC= 9.20600
T1= 376.157745 T2= 416.723511 TEUTFUS= 0.000000

K= 0.0001133682 TAVSTACK= 123.29063 TAVINS= 46.18181
TIME1= 1201.23706 TIME2= 1502.36707 INTTIME= 301.13000
TICASE= -30.5360 TFCASE= -31.3180 TCASE= -30.9270
HLOSS= 0.749782 AVTIME = 1351.802002
XHC= 225.781860 XPAN= 1.00162065
RWX= 17.134007 RWY= 25.751410 SHP= 42.885414

THIGH= 103.0078 TLOW= 64.1592 Fe= 0.1113146
FeO= 0.1719468 KCl= 0.1656636 FeS2= 0.1329144
MgO= 0.2389453 Li= 0.9022734 Al= 0.2222362
LiF= 0.4130158 LiBr= 0.1448168 LiCl= 0.2881079
HPHC= 0.1352901 CUHC= 0.0935647 ECHC= 0.1733733
EUT= 0.2020265 Cu= 0.0935647 XHC= 213.40845
CPINS= 0.2011005 CPHPAP= 0.1400
TSTHC= 5.16334 THPHC= 46.52976 TCUHC= 111.38630
TECHC= 0.00000 TINSHC= 40.91382
TAHC= 0.00000 THPAPC= 8.81628
T1= 337.309235 T2= 376.157745 TEUTFUS= 0.000000

K= 0.0001079013 TAVSTACK= 83.58350 TAVINS= 25.83125
TIME1= 1502.36707 TIME2= 1902.38501 INTTIME= 400.01794
TICASE= -31.3180 TFCASE= -32.5240 TCASE= -31.9210
HLOSS= 0.533497 AVTIME = 1702.375977
XHC= 213.408447 XPAN= 1.00098538
RWX= 17.103355 RWY= 25.702827 SHP= 42.806183

THIGH= 64.1592 TLOW= 31.1833 Fe= 0.1084389
FeO= 0.1690952 KCl= 0.1650800 FeS2= 0.1277909
MgO= 0.2305679 Li= 0.8673481 Al= 0.2182962
LiF= 0.3977211 LiBr= 0.1435680 LiCl= 0.2852274
HPHC= 0.1326194 CUHC= 0.0927169 ECHC= 0.1681013
EUT= 0.1990749 Cu= 0.0927169 XHC= 179.07271
CPINS= 0.1992873 CPHPAP= 0.1400
TSTHC= 4.26960 THPHC= 38.71641 TCUHC= 93.69190
TECHC= 0.00000 TINSHC= 34.41597
TAHC= 0.00000 THPAPC= 7.48357
T1= 304.333252 T2= 337.309235 TEUTFUS= 0.000000

K= 0.0001046212 TAVSTACK= 47.67125 TAVINS= 7.45512
TIME1= 1902.38501 TIME2= 2400.35010 INTTIME= 497.96509
TICASE= -32.5240 TFCASE= -32.9980 TCASE= -32.7610
HLOSS= 0.359609 AVTIME = 2151.367676

XHC= 179.072708 XPAN= 1.00041080
RWX= 17.075703 RWY= 25.658968 SHP= 42.734673

THIGH= 31.1833 TLOW= 15.4720 Fe= 0.1069003
FeO= 0.1667903 KCl= 0.1650792 FeS2= 0.1233457
MgO= 0.2234855 Li= 0.8483019 Al= 0.2156254
LiF= 0.3853190 LiBr= 0.1427215 LiCl= 0.2832749
HPHC= 0.1309693 CUHC= 0.0921422 ECHC= 0.1636724
EUT= 0.1968796 Cu= 0.0921422 XHC= 84.67738
CPINS= 0.1980414 CPHPAP= 0.1400
TSTHC= 2.00537 THPHC= 18.21673 TCUHC= 44.36235
TECHC= 0.00000 TINSHC= 16.29480
TAHC= 0.00000 THPAPC= 3.56551
T1= 288.622009 T2= 304.333252 TEUTFUS= 0.000000

K= 0.0001044416 TAVSTACK= 23.32763 TAVINS= -5.17219
TIME1= 2400.35010 TIME2= 2733.57202 INTTIME= 333.22192
TICASE= -32.9980 TFCASE= -34.3460 TCASE= -33.6720
HLOSS= 0.254117 AVTIME = 2566.960938
XHC= 84.677376 XPAN= 1.00002122
RWX= 17.056980 RWY= 25.629280 SHP= 42.686260

THIGH= 15.4720 TLOW= -5.3860 Fe= 0.1060891
FeO= 0.1647473 KCl= 0.1654097 FeS2= 0.1191920
MgO= 0.2169892 Li= 0.8378765 Al= 0.2136194
LiF= 0.3742983 LiBr= 0.1420857 LiCl= 0.2818083
HPHC= 0.1298644 CUHC= 0.0917106 ECHC= 0.1596289
EUT= 0.1950676 Cu= 0.0917106 XHC= 111.80982
CPINS= 0.1970885 CPHPAP= 0.1400
TSTHC= 2.64209 THPHC= 23.98022 TCUHC= 58.61888
TECHC= 0.00000 TINSHC= 21.52864
TAHC= 0.00000 THPAPC= 4.73352
T1= 267.764008 T2= 288.622009 TEUTFUS= 0.000000

K= 0.0000985565 TAVSTACK= 5.04300 TAVINS= -14.82925
TIME1= 2733.57202 TIME2= 3402.83813 INTTIME= 669.26611
TICASE= -34.3460 TFCASE= -35.0570 TCASE= -34.7015
HLOSS= 0.167063 AVTIME = 3068.205078
XHC= 111.809822 XPAN= 0.99972868
RWX= 17.042946 RWY= 25.607012 SHP= 42.649956

THIGH= -5.3860 TLOW= -18.7105 Fe= 0.1056370
FeO= 0.1625604 KCl= 0.1660130 FeS2= 0.1145850
MgO= 0.2098709 Li= 0.8315808 Al= 0.2117443
LiF= 0.3624807 LiBr= 0.1414914 LiCl= 0.2804375
HPHC= 0.1289511 CUHC= 0.0913071 ECHC= 0.1552119
EUT= 0.1932288 Cu= 0.0913071 XHC= 71.08376
CPINS= 0.1961988 CPHPAP= 0.1400
TSTHC= 1.68063 THPHC= 15.21131 TCUHC= 37.28217
TECHC= 0.00000 TINSHC= 13.69084
TAHC= 0.00000 THPAPC= 3.02386
T1= 254.439499 T2= 267.764008 TEUTFUS= 0.000000

K= 0.0001023108 TAVSTACK= -12.04825 TAVINS= -23.84587
TIME1= 3402.83813 TIME2= 4093.79517 INTTIME= 690.95703
TICASE= -35.0570 TFCASE= -36.2300 TCASE= -35.6435
HLOSS= 0.102877 AVTIME = 3748.316650
XHC= 71.083763 XPAN= 0.99945521
RWX= 17.029837 RWY= 25.586216 SHP= 42.616051

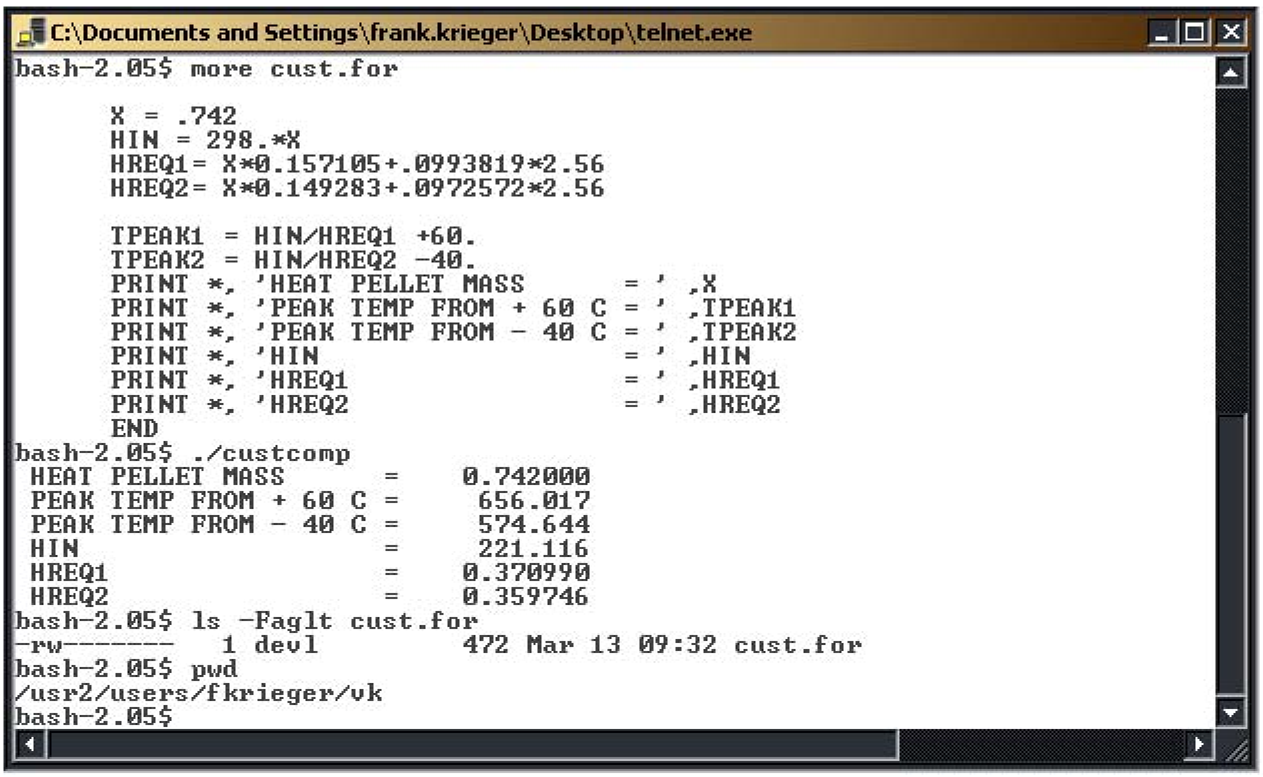
THIGH= -18.7105 TLOW= -23.1050 Fe= 0.1055520
FeO= 0.1612916 KCl= 0.1664693 FeS2= 0.1118433
MgO= 0.2056704 Li= 0.8300005 Al= 0.2107723
LiF= 0.3556151 LiBr= 0.1411833 LiCl= 0.2797269
HPHC= 0.1285360 CUHC= 0.0910979 ECHC= 0.1526113
EUT= 0.1922049 Cu= 0.0910979 XHC= 23.38804
CPINS= 0.1957213 CPHPAP= 0.1400
TSTHC= 0.55383 THPHC= 5.00063 TCUHC= 12.26771
TECHC= 0.00000 TINSHC= 4.50433
TAHC= 0.00000 THPAPC= 0.99729
T1= 250.044998 T2= 254.439499 TEUTFUS= 0.000000

K= 0.0000952303 TAVSTACK= -20.90775 TAVINS= -28.68563
TIME1= 4093.79517 TIME2= 4464.41895 INTTIME= 370.62378
TICASE= -36.2300 TFCASE= -36.6970 TCASE= -36.4635
HLOSS= 0.063105 AVTIME = 4279.106934
XHC= 23.388039 XPAN= 0.99931347
RWX= 17.023046 RWY= 25.575441 SHP= 42.598488

HFUSEC = 17.5326 HFUSA = 7.02 HFUSEUT = 70.2
ECMASS = 0.000 ANODEMASS = 0.000
HPELLETMASS = 8.853 STEELSTACKMASS = 1.194
INSMASS = 10.474 HEAT PAPER MASS =3.242

F-3. Individual Cell Peak Temperature and Heat Balance for a Single Simulated Copper–Heat Pellet Stack Thermal Cell (One Heat Pellet and Four Copper Disks)

The copper–heat pellet simulated thermal cell maximum temperatures were calculated using a program that prints directly to the screen. A picture of program used and the resulting screen printout is included below for convenience. The completed copper–heat pellet stack contained 12 heat pellets (0.742 g each heat pellet) and 48 copper disks (total copper mass = 30.644 g). The specific heats used for copper are effective specific heats from 60 ºC to 600 ºC and from –40 ºC to 520 ºC (*11*).



```
C:\Documents and Settings\frank.krieger\Desktop\telnet.exe
bash-2.05$ more cust.for

      X = .742
      HIN = 298.*X
      HREQ1= X*0.157105+.0993819*2.56
      HREQ2= X*0.149283+.0972572*2.56

      TPEAK1 = HIN/HREQ1 +60.
      TPEAK2 = HIN/HREQ2 -40.
      PRINT *, 'HEAT PELLET MASS      = ' ,X
      PRINT *, 'PEAK TEMP FROM + 60 C = ' ,TPEAK1
      PRINT *, 'PEAK TEMP FROM - 40 C = ' ,TPEAK2
      PRINT *, 'HIN                   = ' ,HIN
      PRINT *, 'HREQ1                 = ' ,HREQ1
      PRINT *, 'HREQ2                 = ' ,HREQ2
      END
bash-2.05$ ./custcomp
 HEAT PELLET MASS      =    0.742000
 PEAK TEMP FROM + 60 C =     656.017
 PEAK TEMP FROM - 40 C =     574.644
 HIN                   =     221.116
 HREQ1                 =    0.370990
 HREQ2                 =    0.359746
bash-2.05$ ls -Faglt cust.for
-rw-------   1 devl         472 Mar 13 09:32 cust.for
bash-2.05$ pwd
/usr2/users/fkrieger/vk
bash-2.05$
```

INTENTIONALLY LEFT BLANK.

Appendix G. Alternate Fortran Programs for Thermal Conductivity Values from Copper–Heat Pellet Stack Cooling Curves in Controlled Gas Atmospheres

Appendix G-1 shows the input file for the ~11 atmosphere ultra-pure carrier grade H_2 gas pressure transient heat transfer experiment using the copper–heat pellet stack. The input columns shown in appendix G-1 represent time (s) and center stack, bottom stack, and case temperatures (ºC), respectively. The top thermocouple was not included because of intermittent irregularities in readings taken from that thermocouple. The stack center and bottom temperatures remained similar throughout the experiment. The RTF was removed from a temperature chamber at 60 ºC and placed into a temperature chamber at 200 ºC to obtain the input data for calculating the global thermal insulation package thermal conductivity values using the source file (appendix G-2). The calculated thermal conductivity data are shown in appendix G-3. The global thermal insulation package thermal conductivity values are shown plotted versus median thermal insulation package temperatures in figure 11 of the main report. Heat contents of other thermal battery materials are again included to facilitate rewriting the source file program for future experiments.

G-1. Input File for Thermal Conductivity Values for the Copper–Heat Pellet Stack Thermal Insulation Package

This is 895 July 23 2008 17:20 kcu12i in /usr2/users/fkrieger/vk on push.

```
203.546     61.052      60.927      62.749
407.091     64.472      64.56       73.728
705.138     77.477      77.501      90.02
1010.46     93.447      93.501      106.493
1308.507    108.581     108.598     120.526
1606.558    122.254     122.253     132.636
1904.604    133.868     133.909     142.743
2202.652    143.99      144.005     151.55
2500.702    152.394     152.406     158.675
2806.019    159.77      159.801     165.181
3104.073    165.826     165.845     170.343
3409.393    170.944     170.974     174.712
3700.17     175.211     175.214     178.452
4107.257    179.989     179.999     182.453
4507.076    183.868     183.854     185.739
4906.897    186.945     186.922     188.323
5401.219    189.802     189.822     190.858
5910.083    192.158     192.15      192.918
7015.047    195.35      195.369     195.703
8505.298    197.372     197.366     197.374
```

G-2. Source File for Thermal Conductivity Values for the Copper–Heat Pellet Stack Thermal Insulation Package

This is 13277 23 July 2008 17:30 kcu12.for on /usr2/users/fkrieger/vk on push.

```
C     This program is rewritten from 12885 July 17 2008 14:58
C     kcu11.for to use the input file kcu12i which is the
C     elevated temperature input file for the transient heating
C     of the copper heat pellet stack in the RTF under 11 atm of
C     UPCG hydrogen. There are no computational changes at all
C     in this program because the top thermocouple data is still
C     faulty.

C  1= Fe      6= LiF(s)      11= LiCl(l)      16= Al(l)
C  2= FeO     7= LiF(l)      12= Cu           17= Heat Pellet
C  3= KCl(s)  8= LiBr(s)     13= Li(s)        18= Anode
C  4= FeS2    9= LiBr(l)     14= Li(l)        19= Elec-Cathode
C  5= MgO     10=LiCl(s)     15= Al(s)        20= Eutectic

C     PR1= Weight fraction Fe, FeO, KCl in burned heat pellet.
C     PR2= Weight fraction LiF, LiBr, LiCl, Li, Al, in anode.
C     PR3= Weight fraction Fe, FeS2, MgO, LiF, LiBr, LiCl, in
C     electrolyte/cathode.
C     GMW= Gram molecular weights of first 16 substances.
C
C     703.15 K = 430 C = Melting point of LiF-LiBr-LiCl eutectic.
C     453.7  K = 180.55 C = Melting point of Lithium.
C     932 K = 658.85 C = Melting point of Aluminum.
C     70.20 cal/g  = Heat of fusion of LiF-LiBr-LiCl eutectic.
C     17.5326 cal/g  = Heat of fusion of LiF-LiBr-KBr eutectic in
C          electrolyte-cathode (70.20*(.0238872+.170860+.0550045)
C          = 17.5326).
C     7.02 cal/g  = Heat of fusion of LiF-LiBr-LiCl eutectic in
C     anode (70.2*(.00956438+.0684120+.0220237)=7.02) (Li(Al)).
C     The experimental cathode uses 45/55 E/B and anode uses only E.
C     The separator uses 53/47 E/B. The E/C composition was
C     calculated using 53/47 E/B for both separators and cathodes.
C     All heat capacities calculated as sum of component
C     heat capacities.
C     Liquid lithium heat capacity used above 453.7 K.
C     Liquid aluminum heat capacity used above 932 K.
C     Heat of fusion of lithium 715/6.94 = 103.026 c/g is ignored.
C     Heat of fusion of aluminum 2570/26.98 = 95.2557 c/g is ignored.
C     T (K) = T (C) + 273.15
```

```
      DIMENSION PR1(16),PR2(16),PR3(16),GMW(16),DELH(21)

      DATA
     1 PR1/0.595687,0.318222,0.0861032,0.,0.,0.,0.,0.,0.,0.,0.,0.,0.,
     1 0.,0.,0./,
     2 PR2/0.,0.,0.,0.,0.,.00956438,0.,.0684120,0.,.0220237,0.,
     3    0.,0.18,0.,0.72,0./,
     4 PR3/0.0132193,0.,0.,0.515552,0.221478,.0238872,0.,.170860,0.,
     5   .0550045,0.,0.,0.,0.,0.,0./,
     6 GMW/55.85,68.89,74.56,119.98,40.32,25.94,25.94,86.85,86.85,
     7 42.39,42.39,63.54,6.94,6.94,26.98,26.98/


      OPEN(UNIT=5,NAME='/usr2/users/fkrieger/vk/kcu12i',TYPE='OLD')
      OPEN(UNIT=6,NAME='/usr2/users/fkrieger/vk/qfile',TYPE='NEW')
      READ(5,111) TI1,TCE1,TB1,TC1
8     READ(5,111,END=219) TI2,TCE2,TB2,TC2
111   FORMAT(F11.7,F12.7,F12.7,F12.7)
      THIGH=(TCE1+TB1)/2.
      TLOW=(TCE2+TB2)/2.
      TCASE=0.5*(TC1+TC2)
      TIME= TI2-TI1
      TM=(THIGH+TLOW)/2.
      TIN=(TM+TCASE)/2.
      T1=TLOW+273.15
      T2=THIGH+273.15
      DO  I=1,5
      IF((T2-T1).EQ.0.) GO TO 19
        DELH(I)=ENTG(T1,T2,I)/GMW(I)/(T2-T1)
      END DO

      DELH(12) = ENTG(T1,T2,12)/GMW(12)/(T2-T1)

          IF(T2.LT.703.15) THEN
            DELH(6) = ENTG(T1,T2,6)/GMW(6)/(T2-T1)
            DELH(8) = ENTG(T1,T2,8)/GMW(8)/(T2-T1)
            DELH(10)= ENTG(T1,T2,10)/GMW(10)/(T2-T1)
          ELSE IF(T1.GT.703.15) THEN
            DELH(6) = ENTG(T1,T2,7)/GMW(7)/(T2-T1)
            DELH(8) = ENTG(T1,T2,9)/GMW(9)/(T2-T1)
            DELH(10)= ENTG(T1,T2,11)/GMW(11)/(T2-T1)
          ELSE
            DELH(6) = ENTG(T1,703.15,6)/GMW(6)/(T2-T1)
     1            + ENTG(703.15,T2,7)/GMW(7)/(T2-T1)
```

```
          DELH(8) = ENTG(T1,703.15,8)/GMW(8)/(T2-T1)
     1          + ENTG(703.15,T2,9)/GMW(9)/(T2-T1)
          DELH(10)= ENTG(T1,703.15,10)/GMW(10)/(T2-T1)
     1          + ENTG(703.15,T2,11)/GMW(11)/(T2-T1)
        END IF
        IF(T2.LT.453.7) THEN
          DELH(13)= ENTG(T1,T2,13)/GMW(13)/(T2-T1)
        ELSE IF(T1.GT.453.7) THEN
          DELH(13)= ENTG(T1,T2,14)/GMW(14)/(T2-T1)
        ELSE
          DELH(13)= ENTG(T1,453.7,13)/GMW(13)/(T2-T1)
     1          + ENTG(453.7,T2,14)/GMW(14)/(T2-T1)
        END IF
        IF(T2.LT.932.0) THEN
          DELH(15)= ENTG(T1,T2,15)/GMW(15)/(T2-T1)
        ELSE IF(T1.GT.932.0) THEN
          DELH(15)= ENTG(T1,T2,16)/GMW(16)/(T2-T1)
        ELSE
          DELH(15)= ENTG(T1,932.0,15)/GMW(15)/(T2-T1)
     1          + ENTG(932.0,T2,16)/GMW(16)/(T2-T1)
        END IF

      DELH(17)=0.0
      DELH(18)=0.0
      DELH(19)=0.0

      DO J=1,16
        DELH(17)=DELH(J)*PR1(J)+DELH(17)
        DELH(18)=DELH(J)*PR2(J)+DELH(18)
        DELH(19)=DELH(J)*PR3(J)+DELH(19)
      END DO

      DELH(20)=.0956438*DELH(6)+.684120*DELH(8)+.220237*DELH(10)

      CPHPAP = 0.14
      CPINS =.1716+.00009867*(TIN+273.15)
C     Expansion of the battery stack components with temperature.
      XPAN=1.+.000016*(TM-22.)
      FL1=.8145*2.54
      FL2=1.23825*2.54
      D1=0.75*2.54
      D2=1.2455*2.54
      PI=3.1415927
      RWX=PI*((D1*XPAN)**2/(FL2-FL1*XPAN)+1.08*D1*XPAN)
      RWY=PI*2.*FL1*XPAN/ALOG(D2/D1/XPAN)
      SHP=RWX+RWY
```

```
      XHC   = (T2-T1)*((1.194*DELH(1)+8.853*DELH(17)
     1+30.644*DELH(12))+(CPHPAP*3.242+CPINS*10.474
     1+0.277*DELH(1))*.5)
C     IF(THIGH.GT.430.01.AND.TLOW.LT.429.99) THEN
C     TEUTFUS=7.02*1.570+17.5326*5.958
C     XHC=XHC+TEUTFUS
C     ELSE
C     TEUTFUS=0.0
C     END IF
      COND= XHC/(SHP*TIME*(TM-TCASE))
      AVTI= (TI1+TI2)/2.
      HLOSS= COND*SHP*(TM-TCASE)

      TSTHC = 1.194*(T2-T1)*DELH(1)
      THPHC = 8.853*(T2-T1)*DELH(17)
      TCUHC = 30.644*(T2-T1)*DELH(12)
C     TECHC = 5.958*(T2-T1)*DELH(19)
      THPAPC= 3.242*(T2-T1)*.5*CPHPAP
      TINSHC= 10.474*(T2-T1)*.5*CPINS
      TCUHC = 30.644*(T2-T1)*DELH(12)


      WRITE(6,220) THIGH,TLOW,DELH(1)
      WRITE(6,221) DELH(2),DELH(3),DELH(4)
      WRITE(6,222) DELH(5),DELH(13),DELH(15)
      WRITE(6,223) DELH(6),DELH(8),DELH(10)
      WRITE(6,224) DELH(17),DELH(12),DELH(19)
      WRITE(6,225) DELH(20),DELH(12),XHC
      WRITE(6,231) CPINS,CPHPAP
      WRITE(6,250) TSTHC,THPHC,TCUHC
      WRITE(6,251) TECHC,TINSHC
      WRITE(6,252) TAHC,THPAPC
      WRITE(6,235) T1,T2,TEUTFUS
      WRITE(6,232) COND,TM,TIN
      WRITE(6,233) TI1,TI2,TIME
      WRITE(6,237) TC1,TC2,TCASE
      WRITE(6,236) HLOSS,AVTI
      WRITE(6,242) XHC,XPAN
      WRITE(6,243) RWX,RWY,SHP


 19   TI1=TI2
C     TT1=TT2
      TCE1=TCE2
      TB1=TB2
```

```
      TC1=TC2
      GO TO 8
 219  WRITE(6,226)
      WRITE(6,227)
      WRITE(6,228)
      WRITE(6,229)
 220  FORMAT(' THIGH=' ,F9.4,' TLOW=',F9.4,' Fe=', F12.7)
 221  FORMAT(' FeO=' ,F12.7,' KCl=',F12.7,' FeS2=', F12.7)
 222  FORMAT(' MgO=' ,F12.7,' Li=' ,F12.7,' Al=', F12.7)
 223  FORMAT(' LiF=', F12.7,' LiBr=',F12.7,' LiCl=', F12.7)
 224  FORMAT(' HPHC=', F12.7,' CUHC=',F12.7,' ECHC=', F12.7)
 225  FORMAT(' EUT=' ,F12.7, ' Cu=',F12.7' XHC=',F15.5)
 226  FORMAT(' HFUSEC = 17.5326  HFUSA = 7.02  HFUSEUT = 70.2')
 227  FORMAT(' ECMASS = 0.000  ANODEMASS = 0.000')
 228  FORMAT(' HPELLETMASS = 8.853  STEELSTACKMASS = 1.194')
 229  FORMAT(' INSMASS = 10.474 HEAT PAPER MASS =3.242')
 231  FORMAT(' CPINS=' ,F12.7, ' CPHPAP=' , F12.4)
 232  FORMAT(' K=' ,F13.10,  ' TAVSTACK= ' ,F12.5, '  TAVINS= ' ,F12.5)
 233  FORMAT(' TIME1=' ,F12.5, ' TIME2= ' ,F12.5, ' INTTIME= ' ,F12.5)
 235  FORMAT(' T1=' ,F12.6,  ' T2= ' ,F12.6, '  TEUTFUS= ' ,F12.6//)
 236  FORMAT(' HLOSS= ' ,F12.6, ' AVTIME = ' , F12.6)
 237  FORMAT(' TICASE= ' ,F10.4,' TFCASE= ' ,F10.4, ' TCASE= ' ,F10.4)
 242  FORMAT(' XHC= ',F12.6,'  XPAN= ',F12.8)
 243  FORMAT(' RWX= ',F15.6,' RWY= ',F15.6,' SHP= ',F15.6//)

 250  FORMAT(' TSTHC=' ,F15.5, ' THPHC=',F15.5, ' TCUHC=',F15.5)
 251  FORMAT(' TECHC=' ,F15.5, ' TINSHC=',F15.5)
 252  FORMAT(' TAHC=' ,F15.5,  ' THPAPC=',F15.5)

 999  CONTINUE
      END

      FUNCTION ENTG(T1,T2,J)
C     This function calculates the molar heat content between T1 and T2.
C     TR1, TR2, TR3 are molar heat capacity coefficients of the first
C     16 substances.

      DIMENSION TR1(16),TR2(16),TR3(16)
      DATA
     2 TR1/ 3.04, 11.66, 9.89, 17.88, 10.18, 10.41, 15.50, 11.50,
     3      16.00, 11.00, 16.00, 5.41, 1.64, 6.78, 4.94, 7.00/,
     4 TR2/ 0.00758, 0.002, 0.0052, 0.00132, .00174, 0.00390, 0.,
     5      0.00302, 0., .0034, 0., .00150, .0111, 0., .00296, 0./,
     6 TR3/ 60000., -67000., 77000.,-305000.,-148000.,-138000., 0.,
     7      0., 0., 0., 0.,0., 84000., 99000., 0., 0./
      ENTG=(T2-T1)*TR1(J)+.5*(T2*T2-T1*T1)*TR2(J)-(1./T2-1./T1)*TR3(J)
```

```
      RETURN
      END
```

G-3. Output file for Thermal Conductivity Values for the Copper–Heat Pellet Stack Thermal Insulation Package (~11 atm H_2 Gas Operating Pressure)

```
This is 17269 July 23 2008 17:31 kcu12o in /usr2/users/fkrieger/vk on push.


THIGH=  60.9895 TLOW=  64.5160 Fe=   0.1095422
 FeO=   0.1703873 KCl=   0.1652247 FeS2=   0.1301896
 MgO=   0.2344428 Li=   0.8808393 Al=   0.2199508
 LiF=   0.4046612 LiBr=   0.1440924 LiCl=   0.2864372
 HPHC=   0.1337002 CUHC=   0.0930729 ECHC=   0.1705326
 EUT=   0.2003639 Cu=   0.0930729 XHC=      -19.33341
 CPINS=   0.2050142 CPHPAP=      0.1400
 TSTHC=       -0.46124 THPHC=       -4.17412 TCUHC=      -10.05800
 TECHC=        0.00000 TINSHC=       -3.78625
 TAHC=        0.00000 THPAPC=       -0.80030
 T1=  337.665985 T2=   334.139496  TEUTFUS=     0.000000


 K= 0.0004048806 TAVSTACK=     62.75275  TAVINS=     65.49562
 TIME1=   203.54601 TIME2=    407.09100 INTTIME=    203.54500
 TICASE=    62.7490 TFCASE=    73.7280 TCASE=    68.2385
 HLOSS=    -0.094983 AVTIME =   305.318512
 XHC=   -19.333412  XPAN=   1.00065207
 RWX=       17.087307 RWY=       25.677376 SHP=       42.764683


 THIGH=  64.5160 TLOW=  77.4890 Fe=   0.1102137
 FeO=   0.1710324 KCl=   0.1653693 FeS2=   0.1313406
 MgO=   0.2363297 Li=   0.8889853 Al=   0.2208559
 LiF=   0.4081205 LiBr=   0.1443793 LiCl=   0.2870988
 HPHC=   0.1343180 CUHC=   0.0932677 ECHC=   0.1717209
 EUT=   0.2010367 Cu=   0.0932677 XHC=      -71.35568
 CPINS=   0.2060939 CPHPAP=      0.1400
 TSTHC=       -1.70718 THPHC=      -15.42641 TCUHC=      -37.07804
 TECHC=        0.00000 TINSHC=      -14.00193
 TAHC=        0.00000 THPAPC=       -2.94409
 T1=  350.638977 T2=   337.665985  TEUTFUS=     0.000000


 K= 0.0005147575 TAVSTACK=     71.00250  TAVINS=     76.43825
 TIME1=   407.09100 TIME2=    705.13800 INTTIME=    298.04700
 TICASE=    73.7280 TFCASE=    90.0200 TCASE=    81.8740
```

HLOSS= -0.239411 AVTIME = 556.114502
XHC= -71.355682 XPAN= 1.00078404
RWX= 17.093658 RWY= 25.687450 SHP= 42.781109

THIGH= 77.4890 TLOW= 93.4740 Fe= 0.1114622
FeO= 0.1721016 KCl= 0.1656902 FeS2= 0.1331957
MgO= 0.2394033 Li= 0.9040689 Al= 0.2224444
LiF= 0.4138463 LiBr= 0.1448828 LiCl= 0.2882601
HPHC= 0.1354295 CUHC= 0.0936095 ECHC= 0.1736612
EUT= 0.2021846 Cu= 0.0936095 XHC= -88.40157
CPINS= 0.2076164 CPHPAP= 0.1400
TSTHC= -2.12738 THPHC= -19.16535 TCUHC= -45.85412
TECHC= 0.00000 TINSHC= -17.38030
TAHC= 0.00000 THPAPC= -3.62764
T1= 366.623993 T2= 350.638977 TEUTFUS= 0.000000

K= 0.0005294149 TAVSTACK= 85.48150 TAVINS= 91.86900
TIME1= 705.13800 TIME2= 1010.46002 INTTIME= 305.32202
TICASE= 90.0200 TFCASE= 106.4930 TCASE= 98.2565
HLOSS= -0.289536 AVTIME = 857.799011
XHC= -88.401573 XPAN= 1.00101566
RWX= 17.104818 RWY= 25.705143 SHP= 42.809959

THIGH= 93.4740 TLOW= 108.5895 Fe= 0.1128918
FeO= 0.1731693 KCl= 0.1661202 FeS2= 0.1349778
MgO= 0.2424005 Li= 0.9212695 Al= 0.2241504
LiF= 0.4195557 LiBr= 0.1454235 LiCl= 0.2895074
HPHC= 0.1366579 CUHC= 0.0939766 ECHC= 0.1755601
EUT= 0.2033752 Cu= 0.0939766 XHC= -84.07646
CPINS= 0.2091361 CPHPAP= 0.1400
TSTHC= -2.03746 THPHC= -18.28724 TCUHC= -43.52992
TECHC= 0.00000 TINSHC= -16.55520
TAHC= 0.00000 THPAPC= -3.43031
T1= 381.739502 T2= 366.623993 TEUTFUS= 0.000000

K= 0.0005277089 TAVSTACK= 101.03175 TAVINS= 107.27063
TIME1= 1010.46002 TIME2= 1308.50696 INTTIME= 298.04694
TICASE= 106.4930 TFCASE= 120.5260 TCASE= 113.5095
HLOSS= -0.282091 AVTIME = 1159.483521
XHC= -84.076462 XPAN= 1.00126445
RWX= 17.116812 RWY= 25.724155 SHP= 42.840965

THIGH= 108.5895 TLOW= 122.2535 Fe= 0.1142861
FeO= 0.1740929 KCl= 0.1665867 FeS2= 0.1364582
MgO= 0.2449306 Li= 0.9379904 Al= 0.2257292
LiF= 0.4244860 LiBr= 0.1459239 LiCl= 0.2906616
HPHC= 0.1378226 CUHC= 0.0943163 ECHC= 0.1771689
EUT= 0.2044433 Cu= 0.0943163 XHC= -76.40826
CPINS= 0.2104909 CPHPAP= 0.1400
TSTHC= -1.86456 THPHC= -16.67204 TCUHC= -39.49208
TECHC= 0.00000 TINSHC= -15.06239
TAHC= 0.00000 THPAPC= -3.10091
T1= 395.403503 T2= 381.739502 TEUTFUS= 0.000000

K= 0.0005358635 TAVSTACK= 115.42149 TAVINS= 121.00125
TIME1= 1308.50696 TIME2= 1606.55798 INTTIME= 298.05103
TICASE= 120.5260 TFCASE= 132.6360 TCASE= 126.5810
HLOSS= -0.256360 AVTIME = 1457.532471
XHC= -76.408264 XPAN= 1.00149477
RWX= 17.127928 RWY= 25.741776 SHP= 42.869705

THIGH= 122.2535 TLOW= 133.8885 Fe= 0.1155605
FeO= 0.1748606 KCl= 0.1670436 FeS2= 0.1376442
MgO= 0.2469879 Li= 0.9532376 Al= 0.2271169
LiF= 0.4285783 LiBr= 0.1463637 LiCl= 0.2916761
HPHC= 0.1388654 CUHC= 0.0946149 ECHC= 0.1784815
EUT= 0.2053591 Cu= 0.0946149 XHC= -65.36714
CPINS= 0.2116630 CPHPAP= 0.1400
TSTHC= -1.60539 THPHC= -14.30375 TCUHC= -33.73422
TECHC= 0.00000 TINSHC= -12.89713
TAHC= 0.00000 THPAPC= -2.64044
T1= 407.038483 T2= 395.403503 TEUTFUS= 0.000000

K= 0.0005315716 TAVSTACK= 128.07098 TAVINS= 132.88025
TIME1= 1606.55798 TIME2= 1904.60400 INTTIME= 298.04602
TICASE= 132.6360 TFCASE= 142.7430 TCASE= 137.6895
HLOSS= -0.219319 AVTIME = 1755.581055
XHC= -65.367142 XPAN= 1.00169718
RWX= 17.137703 RWY= 25.757273 SHP= 42.894974

THIGH= 133.8885 TLOW= 143.9975 Fe= 0.1166881
FeO= 0.1754913 KCl= 0.1674675 FeS2= 0.1385871
MgO= 0.2486459 Li= 0.9667070 Al= 0.2283097

LiF= 0.4319358 LiBr= 0.1467418 LiCl= 0.2925481
HPHC= 0.1397743 CUHC= 0.0948716 ECHC= 0.1795425
EUT= 0.2061309 Cu= 0.0948716 XHC= -57.02314
CPINS= 0.2126659 CPHPAP= 0.1400
TSTHC= -1.40844 THPHC= -12.50910 TCUHC= -29.38936
TECHC= 0.00000 TINSHC= -11.25872
TAHC= 0.00000 THPAPC= -2.29414
T1= 417.147491 T2= 407.038483 TEUTFUS= 0.000000

K= 0.0005434242 TAVSTACK= 138.94299 TAVINS= 143.04474
TIME1= 1904.60400 TIME2= 2202.65210 INTTIME= 298.04810
TICASE= 142.7430 TFCASE= 151.5500 TCASE= 147.1465
HLOSS= -0.191322 AVTIME = 2053.627930
XHC= -57.023144 XPAN= 1.00187111
RWX= 17.146111 RWY= 25.770594 SHP= 42.916702

THIGH= 143.9975 TLOW= 152.4000 Fe= 0.1176691
FeO= 0.1760091 KCl= 0.1678484 FeS2= 0.1393401
MgO= 0.2499857 Li= 0.9784104 Al= 0.2293252
LiF= 0.4346904 LiBr= 0.1470636 LiCl= 0.2932906
HPHC= 0.1405562 CUHC= 0.0950901 ECHC= 0.1804020
EUT= 0.2067780 Cu= 0.0950901 XHC= -47.55981
CPINS= 0.2135156 CPHPAP= 0.1400
TSTHC= -1.18053 THPHC= -10.45560 TCUHC= -24.48437
TECHC= 0.00000 TINSHC= -9.39551
TAHC= 0.00000 THPAPC= -1.90686
T1= 425.549988 T2= 417.147491 TEUTFUS= 0.000000

K= 0.0005375557 TAVSTACK= 148.19875 TAVINS= 151.65562
TIME1= 2202.65210 TIME2= 2500.70190 INTTIME= 298.04980
TICASE= 151.5500 TFCASE= 158.6750 TCASE= 155.1125
HLOSS= -0.159570 AVTIME = 2351.677002
XHC= -47.559807 XPAN= 1.00201917
RWX= 17.153271 RWY= 25.781944 SHP= 42.935215

THIGH= 152.4000 TLOW= 159.7855 Fe= 0.1185198
FeO= 0.1764381 KCl= 0.1681868 FeS2= 0.1399493
MgO= 0.2510805 Li= 0.9885492 Al= 0.2301912
LiF= 0.4369702 LiBr= 0.1473381 LiCl= 0.2939237
HPHC= 0.1412286 CUHC= 0.0952764 ECHC= 0.1811060
EUT= 0.2073233 Cu= 0.0952764 XHC= -41.92597
CPINS= 0.2142413 CPHPAP= 0.1400

TSTHC= -1.04514 THPHC= -9.23406 TCUHC= -21.56307
TECHC= 0.00000 TINSHC= -8.28639
TAHC= 0.00000 THPAPC= -1.67606
T1= 432.935486 T2= 425.549988 TEUTFUS= 0.000000

K= 0.0005478956 TAVSTACK= 156.09274 TAVINS= 159.01038
TIME1= 2500.70190 TIME2= 2806.01904 INTTIME= 305.31714
TICASE= 158.6750 TFCASE= 165.1810 TCASE= 161.9280
HLOSS= -0.137319 AVTIME = 2653.360352
XHC= -41.925968 XPAN= 1.00214553
RWX= 17.159384 RWY= 25.791634 SHP= 42.951019

THIGH= 159.7855 TLOW= 165.8355 Fe= 0.1192529
FeO= 0.1767947 KCl= 0.1684836 FeS2= 0.1404455
MgO= 0.2519801 Li= 0.9972812 Al= 0.2309281
LiF= 0.4388638 LiBr= 0.1475717 LiCl= 0.2944624
HPHC= 0.1418043 CUHC= 0.0954350 ECHC= 0.1816855
EUT= 0.2077828 Cu= 0.0954350 XHC= -34.43049
CPINS= 0.2148605 CPHPAP= 0.1400
TSTHC= -0.86145 THPHC= -7.59515 TCUHC= -17.69334
TECHC= 0.00000 TINSHC= -6.80763
TAHC= 0.00000 THPAPC= -1.37299
T1= 438.985504 T2= 432.935486 TEUTFUS= 0.000000

K= 0.0005430039 TAVSTACK= 162.81050 TAVINS= 165.28625
TIME1= 2806.01904 TIME2= 3104.07300 INTTIME= 298.05396
TICASE= 165.1810 TFCASE= 170.3430 TCASE= 167.7620
HLOSS= -0.115518 AVTIME = 2955.045898
XHC= -34.430489 XPAN= 1.00225294
RWX= 17.164583 RWY= 25.799868 SHP= 42.964451

THIGH= 165.8355 TLOW= 170.9590 Fe= 0.1198692
FeO= 0.1770856 KCl= 0.1687367 FeS2= 0.1408434
MgO= 0.2527071 Li= 1.0046180 Al= 0.2315412
LiF= 0.4404081 LiBr= 0.1477660 LiCl= 0.2949107
HPHC= 0.1422859 CUHC= 0.0955669 ECHC= 0.1821546
EUT= 0.2081622 Cu= 0.0955669 XHC= -29.21819
CPINS= 0.2153712 CPHPAP= 0.1400
TSTHC= -0.73330 THPHC= -6.45386 TCUHC= -15.00445
TECHC= 0.00000 TINSHC= -5.77880
TAHC= 0.00000 THPAPC= -1.16273
T1= 444.109009 T2= 438.985504 TEUTFUS= 0.000000

K= 0.0005391372 TAVSTACK=   168.39725 TAVINS=   170.46237
TIME1= 3104.07300 TIME2=   3409.39307 INTTIME=   305.32007
TICASE=   170.3430 TFCASE=   174.7120 TCASE=   172.5275
HLOSS=   -0.095697 AVTIME = 3256.732910
XHC=   -29.218189 XPAN=   1.00234234
RWX=   17.168913 RWY=   25.806730 SHP=   42.975643

THIGH= 170.9590 TLOW= 175.2125 Fe=   0.1203901
FeO=   0.1773261 KCl=   0.1689528 FeS2=   0.1411678
MgO=   0.2533034 Li=   1.0108166 Al=   0.2320555
LiF=   0.4416839 LiBr=   0.1479290 LiCl=   0.2952867
HPHC=   0.1426913 CUHC=   0.0956776 ECHC=   0.1825398
EUT=   0.2084786 Cu=   0.0956776 XHC=   -24.29888
CPINS=   0.2158026 CPHPAP=   0.1400
TSTHC=   -0.61142 THPHC=   -5.37319 TCUHC=   -12.47096
TECHC=   0.00000 TINSHC=   -4.80710
TAHC=   0.00000 THPAPC=   -0.96528
T1= 448.362488 T2=   444.109009 TEUTFUS=   0.000000

K= 0.0005560415 TAVSTACK=   173.08575 TAVINS=   174.83388
TIME1= 3409.39307 TIME2=   3700.16992 INTTIME=   290.77686
TICASE=   174.7120 TFCASE=   178.4520 TCASE=   176.5820
HLOSS=   -0.083565 AVTIME = 3554.781494
XHC=   -24.298882 XPAN=   1.00241733
RWX=   17.172546 RWY=   25.812485 SHP=   42.985031

THIGH= 175.2125 TLOW= 179.9940 Fe=   0.1208957
FeO=   0.1775546 KCl=   0.1691645 FeS2=   0.1414719
MgO=   0.2538656 Li=   1.0168304 Al=   0.2325511
LiF=   0.4428954 LiBr=   0.1480861 LiCl=   0.2956490
HPHC=   0.1430834 CUHC=   0.0957842 ECHC=   0.1829035
EUT=   0.2087817 Cu=   0.0957842 XHC=   -27.36108
CPINS=   0.2162164 CPHPAP=   0.1400
TSTHC=   -0.69021 THPHC=   -6.05680 TCUHC=   -14.03470
TECHC=   0.00000 TINSHC=   -5.41421
TAHC=   0.00000 THPAPC=   -1.08511
T1= 453.143982 T2=   448.362488 TEUTFUS=   0.000000

K= 0.0005486627 TAVSTACK=   177.60324 TAVINS=   179.02786
TIME1= 3700.16992 TIME2=   4107.25684 INTTIME=   407.08691

TICASE= 178.4520 TFCASE= 182.4530 TCASE= 180.4525
HLOSS= -0.067212 AVTIME = 3903.713379
XHC= -27.361082 XPAN= 1.00248969
RWX= 17.176052 RWY= 25.818041 SHP= 42.994095

THIGH= 179.9940 TLOW= 183.8610 Fe= 0.1213826
FeO= 0.1777708 KCl= 0.1693699 FeS2= 0.1417564
MgO= 0.2543944 Li= 1.0226198 Al= 0.2330256
LiF= 0.4440416 LiBr= 0.1482365 LiCl= 0.2959959
HPHC= 0.1434599 CUHC= 0.0958863 ECHC= 0.1832459
EUT= 0.2090706 Cu= 0.0958863 XHC= -22.16357
CPINS= 0.2166095 CPHPAP= 0.1400
TSTHC= -0.56045 THPHC= -4.91129 TCUHC= -11.36258
TECHC= 0.00000 TINSHC= -4.38667
TAHC= 0.00000 THPAPC= -0.87758
T1= 457.010986 T2= 453.143982 TEUTFUS= 0.000000

K= 0.0005944517 TAVSTACK= 181.92749 TAVINS= 183.01175
TIME1= 4107.25684 TIME2= 4507.07617 INTTIME= 399.81934
TICASE= 182.4530 TFCASE= 185.7390 TCASE= 184.0960
HLOSS= -0.055434 AVTIME = 4307.166504
XHC= -22.163568 XPAN= 1.00255883
RWX= 17.179405 RWY= 25.823351 SHP= 43.002754

THIGH= 183.8610 TLOW= 186.9335 Fe= 0.1217752
FeO= 0.1779423 KCl= 0.1695367 FeS2= 0.1419797
MgO= 0.2548113 Li= 1.0447894 Al= 0.2334062
LiF= 0.4449504 LiBr= 0.1483571 LiCl= 0.2962742
HPHC= 0.1437627 CUHC= 0.0959682 ECHC= 0.1835161
EUT= 0.2093013 Cu= 0.0959682 XHC= -17.63260
CPINS= 0.2169255 CPHPAP= 0.1400
TSTHC= -0.44674 THPHC= -3.91048 TCUHC= -9.03579
TECHC= 0.00000 TINSHC= -3.49049
TAHC= 0.00000 THPAPC= -0.69728
T1= 460.083496 T2= 457.010986 TEUTFUS= 0.000000

K= 0.0006276196 TAVSTACK= 185.39725 TAVINS= 186.21413
TIME1= 4507.07617 TIME2= 4906.89697 INTTIME= 399.82080
TICASE= 185.7390 TFCASE= 188.3230 TCASE= 187.0310
HLOSS= -0.044101 AVTIME = 4706.986328
XHC= -17.632599 XPAN= 1.00261438
RWX= 17.182098 RWY= 25.827614 SHP= 43.009712

THIGH= 186.9335 TLOW= 189.8120 Fe= 0.1221131
FeO= 0.1780881 KCl= 0.1696809 FeS2= 0.1421679
MgO= 0.2551642 Li= 1.0439167 Al= 0.2337325
LiF= 0.4457229 LiBr= 0.1484605 LiCl= 0.2965126
HPHC= 0.1440228 CUHC= 0.0960384 ECHC= 0.1837450
EUT= 0.2094985 Cu= 0.0960384 XHC= -16.53749
CPINS= 0.2171985 CPHPAP= 0.1400
TSTHC= -0.41970 THPHC= -3.67020 TCUHC= -8.47146
TECHC= 0.00000 TINSHC= -3.27421
TAHC= 0.00000 THPAPC= -0.65325
T1= 462.962006 T2= 460.083496 TEUTFUS= 0.000000

K= 0.0006386710 TAVSTACK= 188.37276 TAVINS= 188.98163
TIME1= 4906.89697 TIME2= 5401.21924 INTTIME= 494.32227
TICASE= 188.3230 TFCASE= 190.8580 TCASE= 189.5905
HLOSS= -0.033455 AVTIME = 5154.058105
XHC= -16.537495 XPAN= 1.00266194
RWX= 17.184402 RWY= 25.831268 SHP= 43.015671

THIGH= 189.8120 TLOW= 192.1540 Fe= 0.1224112
FeO= 0.1782152 KCl= 0.1698088 FeS2= 0.1423304
MgO= 0.2554702 Li= 1.0431660 Al= 0.2340191
LiF= 0.4463958 LiBr= 0.1485514 LiCl= 0.2967222
HPHC= 0.1442518 CUHC= 0.0961001 ECHC= 0.1839436
EUT= 0.2096712 Cu= 0.0961001 XHC= -13.46812
CPINS= 0.2174406 CPHPAP= 0.1400
TSTHC= -0.34230 THPHC= -2.99085 TCUHC= -6.89688
TECHC= 0.00000 TINSHC= -2.66690
TAHC= 0.00000 THPAPC= -0.53149
T1= 465.303986 T2= 462.962006 TEUTFUS= 0.000000

K= 0.0006797949 TAVSTACK= 190.98300 TAVINS= 191.43550
TIME1= 5401.21924 TIME2= 5910.08301 INTTIME= 508.86377
TICASE= 190.8580 TFCASE= 192.9180 TCASE= 191.8880
HLOSS= -0.026467 AVTIME = 5655.651367
XHC= -13.468123 XPAN= 1.00270379
RWX= 17.186434 RWY= 25.834484 SHP= 43.020920

THIGH= 192.1540 TLOW= 195.3595 Fe= 0.1227284
FeO= 0.1783492 KCl= 0.1699454 FeS2= 0.1425007

MgO=   0.2557916 Li=   1.0423819 Al=   0.2343233
LiF=   0.4471051 LiBr=   0.1486478 LiCl=   0.2969446
HPHC=   0.1444952 CUHC=   0.0961656 ECHC=   0.1841525
EUT=   0.2098539 Cu=   0.0961656 XHC=   -18.45303
CPINS=   0.2176970 CPHPAP=   0.1400
TSTHC=   -0.46973 THPHC=   -4.10053 TCUHC=   -9.44630
TECHC=   0.00000 TINSHC=   -3.65453
TAHC=   0.00000 THPAPC=   -0.72746
T1= 468.509491 T2=   465.303986 TEUTFUS=   0.000000

K= 0.0007009141 TAVSTACK=   193.75674 TAVINS=   194.03363
TIME1= 5910.08301 TIME2=   7015.04688 INTTIME=   1104.96387
TICASE=   192.9180 TFCASE=   195.7030 TCASE=   194.3105
HLOSS=   -0.016700 AVTIME = 6462.564941
XHC=   -18.453030 XPAN=   1.00274813
RWX=   17.188583 RWY=   25.837891 SHP=   43.026474

THIGH= 195.3595 TLOW= 197.3690 Fe=   0.1230277
FeO=   0.1784742 KCl=   0.1700748 FeS2=   0.1426585
MgO=   0.2560906 Li=   1.0416572 Al=   0.2346094
LiF=   0.4477674 LiBr=   0.1487384 LiCl=   0.2971538
HPHC=   0.1447244 CUHC=   0.0962271 ECHC=   0.1843468
EUT=   0.2100254 Cu=   0.0962271 XHC=   -11.57915
CPINS=   0.2179356 CPHPAP=   0.1400
TSTHC=   -0.29518 THPHC=   -2.57465 TCUHC=   -5.92555
TECHC=   0.00000 TINSHC=   -2.29349
TAHC=   0.00000 THPAPC=   -0.45603
T1= 470.518982 T2=   468.509491 TEUTFUS=   0.000000

K= 0.0010361979 TAVSTACK=   196.36424 TAVINS=   196.45137
TIME1= 7015.04688 TIME2=   8505.29785 INTTIME=   1490.25098
TICASE=   195.7030 TFCASE=   197.3740 TCASE=   196.5385
HLOSS=   -0.007770 AVTIME = 7760.172363
XHC=   -11.579153 XPAN=   1.00278986
RWX=   17.190607 RWY=   25.841095 SHP=   43.031700

HFUSEC = 17.5326 HFUSA = 7.02 HFUSEUT = 70.2
ECMASS = 0.000 ANODEMASS = 0.000
HPELLETMASS = 8.853 STEELSTACKMASS = 1.194
INSMASS = 10.474 HEAT PAPER MASS =3.242

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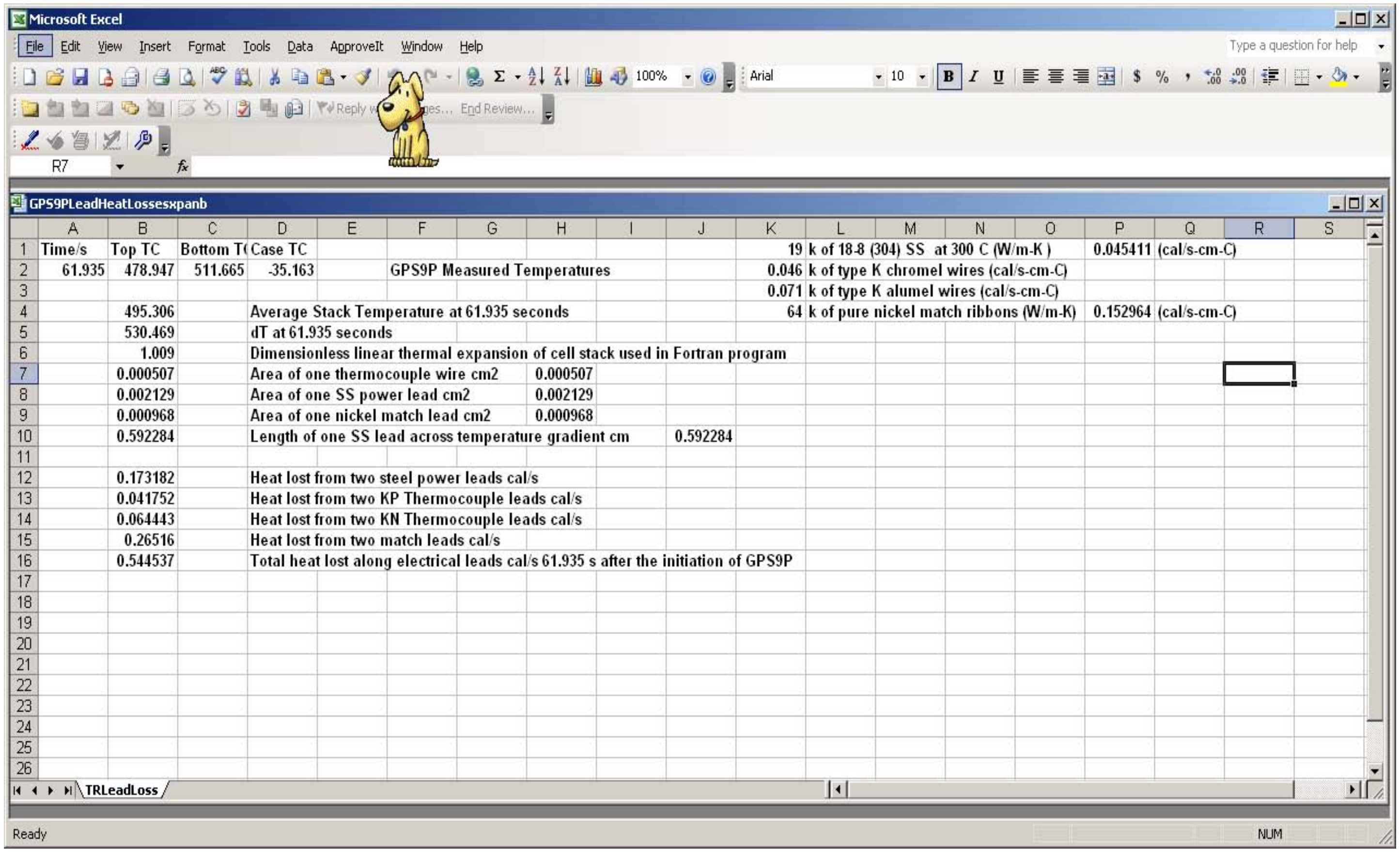
Appendix H. Estimated Heat Loss Rates Along the GPS9P Electrical Leads

The heat loss rates along the GPS9P and GPS9Q electrical and thermocouple leads can be estimated from the lead cross-sectional areas and lengths across the temperature gradients. Heat loss estimates below are calculated to six significant figures to facilitate debugging of future Fortran programs.

Using numbers for GPS9P in appendix B, the length of the SS leads across the temperature gradient can be estimated as half the difference between the average length of the cell stack height after allowing for the 1.009 thermal expansion factor of heating for the cell stack on battery initiation (0.5x(.760+.770)x1.009= 0.771885 in.) and the average inner length of the RTF (.5x(1.237+1.2395)=1.23825 in.). The estimated length of the leads across the temperature gradient is then 0.5x(1.23825–.771885)=0.233183 in. or 0.592285 cm. The SS leads were ~0.110 in. wide x 0.003 in. thick, with a cross-sectional area of ~0.00212903 cm^2 for one lead. The cross-sectional area of one of the 0.010 in. diameter thermocouple wires was 0.000506707 cm^2, and the cross-sectional area of one of the ~0.050 in. x 0.003 in. match leads was ~0.000967740 cm^2. The thermal conductivity of the 304 SS leads at 300 ºC was estimated at 19 W/m-ºK or 19/418.4= .0454111 cal/s-cm ºC. The thermal conductivities of the type K thermocouple wires KN and KP were estimated at 0.071 and 0.046 cal/s-cm-ºC respectively. The thermal conductivity of the pure nickel ribbons was estimated at 64 W/m-ºK or 0.152964 cal/s-cm-ºC.

At 61.935 s after initiation of GPS9P the temperature gradient between the cell stack and the RTF was 530.469 ºC. The heat loss from the two steel leads can then be estimated as 2xkAdT/dx = 2x0.0454111 cal/s-cm-ºC x 0.00212903 cm^2 x 530.469 ºC/0.592285 cm = 0.173182 cal/s. Heat loss rates at 61.935 s are estimated for the two power leads, the two match leads, and the four thermocouple wires, as shown in the Excel spreadsheet below. The total amount of heat loss from all the electrical leads is 0.544537 cal/s. The heat loss along the electrical leads is large enough that it can become an engineering consideration in small thermal batteries with highly efficient thermal insulators. A picture of an Excel spread sheet showing the calculations is shown below for convenience.



	A	B	C	D	E	F	G	H	I	J	K	L	M	N	O	P	Q	R	S
1	Time/s	Top TC	Bottom T(	Case TC							19	k of 18-8 (304) SS at 300 C (W/m-K)				0.045411	(cal/s-cm-C)		
2	61.935	478.947	511.665	-35.163		GPS9P Measured Temperatures					0.046	k of type K chromel wires (cal/s-cm-C)							
3											0.071	k of type K alumel wires (cal/s-cm-C)							
4		495.306		Average Stack Temperature at 61.935 seconds							64	k of pure nickel match ribbons (W/m-K)				0.152964	(cal/s-cm-C)		
5		530.469		dT at 61.935 seconds															
6		1.009		Dimensionless linear thermal expansion of cell stack used in Fortran program															
7		0.000507		Area of one thermocouple wire cm2				0.000507											
8		0.002129		Area of one SS power lead cm2				0.002129											
9		0.000968		Area of one nickel match lead cm2				0.000968											
10		0.592284		Length of one SS lead across temperature gradient cm						0.592284									
11																			
12		0.173182		Heat lost from two steel power leads cal/s															
13		0.041752		Heat lost from two KP Thermocouple leads cal/s															
14		0.064443		Heat lost from two KN Thermocouple leads cal/s															
15		0.26516		Heat lost from two match leads cal/s															
16		0.544537		Total heat lost along electrical leads cal/s 61.935 s after the initiation of GPS9P															
17																			
18																			
19																			
20																			
21																			
22																			
23																			
24																			
25																			
26																			

Appendix I. Estimated I^2R Heating from GPS9P Internal Battery Resistance and Electrical Leads

Estimated I^2R heating quantities in this appendix are calculated to six significant figures to facilitate debugging of future Fortran programs. Figure 6 shows that the internal resistance of the battery is significantly larger than the internal resistance of the lead wires. The battery showed an internal resistance of about 0.6 ohm after 60 s of discharge. The I^2R heating for the battery itself would then be 0.6x1.5x1.5/4.184=0.322658 cal/s (1 calorie = 4.184 watt-seconds).

A steel manufacturing company reported the resistance of 304 L SS as 95 micro-ohm-cm at 600 °F. The total length of the positive and negative leads is estimated as the combined length of both leads across the temperature gradient in appendix H above plus the length of the thermal cell stack (0.592285x2+0.675x2.54= 2.89907 cm). The cross-sectional area of the 304 L SS leads was ~0.110x0.003x2.54^2= 0.00212903 cm^2. The total estimated lead resistance during battery operation is then 2.89907/.00212903x95E-6=0.129360 ohm. The total estimated I^2R heating at 1.5 A constant current for both of the SS leads is 0.129360 x 1.5 x 1.5 /4.184 = 0.0695650 cal/s.

These calculations show that the I^2R heating of the battery itself, and that of the lead wires, can both become significant factors in small thermal batteries with good thermal insulators. Ohmic heating from the thermal cell stack during operation appears to offer an attractive contribution to heat transfer engineering problems in many of these situations.

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Appendix J. Possible Case Dimensions (Calculated Battery Volumes) of Thermal Batteries with Previously Optimized Electrochemical-Heat Source Stacks

Table 2 in the main report illustrates the degree of experimental effort required to optimize thermal cell electrochemical-heat source stacks. The source program below permits the calculation of thermal lifetimes using previously optimized electrochemical-heat source stacks while changing outer case dimensions and/or global thermal insulation package thermal conductivity values.

For the source program below the optimized cell stack parameters do not change. The inner case lengths and diameters and/or insulation package thermal conductivity values are changed manually, after which the corresponding thermal lifetimes are calculated.

J–1. Input File

This is 239 19 September 2008 19:09 gnft2si.

```
 435.       600.      -40.       60.
   7.86      4.2       1.509    3.17908
  2.91000    224.      112.
  2.91000   1.9050    .662940   .548640   .121920
  3.9000E-4  0.6000E-7   3.9000E-4   0.6000E-7
   1.009     0.0
```

J-2. Source Program

This is 44148 19 September 2008 18:56 gnft2s.for. Initial comments in the main program have been removed in the interest of brevity. This is the program that produced 14616 19 September 2008 19:09 gnft2so.

```
C*****************************************************************
C                  This is the main program
C*****************************************************************

C     TMINOP =Minimum cell  operating temperature  (C).
C     TMAXOP =Maximum cell operating temperature (C).
C     TAL    =Lowest ambient temperature (C).
C     TAH    =Highest  ambient  temperature  (C).
C     DENFE  =Density of iron (g/cm3).
C     DENHP  =Density of  heat pellet  (g/cm3).
C     DENA   =Density of anode (g/cm3).
```

```
C     DENEC  =Density of electrolyte-cathode (g/cm3).
C     FL3    =Inner length of outer case (cm).
C     HGF    =Total heat generated by thermal cells during first
C            cooling interval (cal).
C     HGB    =Total heat generated by thermal cells during second
C            cooling interval (cal).
C     D3     =Inner diameter of outer case (cm).
C     D2     =Outer diameter of heat reservoir (cm).
C     HEC    =Total height of electrolyte-cathodes (cm).
C     HA     =Total height of anodes (cm).
C     HFEST  =Total height of iron cell covers in stack (cm).
C     GK4,GB4=Thermal conductivity coefficients for end insulation.
C          K= GK4+GB4*TM, where K is thermal conductivity
C            (cal/sec-cm-C) and TM is the effective insulation
C            temperature TM=1/2(Tcell+Tcase) in degrees C.
C     GK5,GB5=Thermal conductivity coefficients for side insulation.
C     XPAN   =Thermal expansion factor for cells and reservoir
C            (dimensionless).
C     DH     =Diameter of center hole (cm).

      COMMON /SUBSTN/ FEHC,HPHC,AHC,ECHC
      COMMON /CALC/   PI,PQ,D2P,VEC,VA,VFEST,CHX,CA(6),CB(6),CC(6),
     1               CD(6),CE(6),CF(6),VHPST,HHPST,FL1,V1,P,FP,FI,
     2               FPE,FPS,VPIE,VPIS,CTX
      COMMON /DAT/    TMINOP,TMAXOP,TAL,TAH,D3,D2,GK4,GB4,END,SIDE,
     1               GK5,GB5,XPAN,DH,TIMEX,HGF,HGB
      COMMON /DNCITY/ DENFE,DENHP,DENA,DENEC
      COMMON /VERFY/  VFERS,VHPRS,FL2SV,FL3SV,VENDI,VSIDEI,CD1,CD2,CD3,
     1               CR1,CR2,CR3,TI1,TI2,TI3,TH1,TH2,TQM,RWX,RWY,R1,
     2               R2,R3,DT1,DT2,DT3,W1,W2,W3,T1,T2,T3
      NAMELIST/HERIN/ TMINOP,TMAXOP,TAL,TAH,DENFE,DENHP,DENA,DENEC,
     1               FL3,HGF,HGB,D2,D3,HEC,HA,HFEST,GK4,GB4,GK5,GB5,
     2               XPAN,DH
C
      OPEN(UNIT=5,NAME='/usr2/users/fkrieger/vk/gnft2si',TYPE='OLD')
      OPEN(UNIT=6,NAME='/usr2/users/fkrieger/vk/qfile',TYPE='NEW')
C
      READ(5,501) TMINOP,TMAXOP,TAL,TAH
      READ(5,501) DENFE,DENHP,DENA,DENEC
      READ(5,501) FL3,HGF,HGB
      READ(5,501) D3,D2,HEC,HA,HFEST
      READ(5,502) GK4,GB4,GK5,GB5
      READ(5,503) XPAN,DH
 501  FORMAT(8F10.5)
 502  FORMAT(4E12.3)
 503  FORMAT(2F10.5)
```

```
      WRITE(6,HERIN)
      PI=3.141592654
      PQ=PI/4.
      D2P=D2*D2-DH*DH
      VEC=PQ*D2P*HEC
      VA=PQ*D2P*HA
      VFEST=PQ*D2P*HFEST
      CHX=298.0*DENHP

C     Added Statements Here

      FL2=1.952915
      FL2SV=1.952915
      VENDI=PQ*(FL3-FL2)*D3**2
      VSIDEI=PQ*FL2*(D3**2-D2**2)
      VOLINS=VENDI+VSIDEI

C     End Added Statements Here

      CALL MATERL(TAH,TMAXOP)
      CA(1)=ECHC
      CA(2)=FEHC
      CA(3)=HPHC
      CA(4)=AHC
      CA(5)=END
      CA(6)=SIDE
      CALL MATERL(TAL,TMINOP)
      CB(1)=ECHC
      CB(2)=FEHC
      CB(3)=HPHC
      CB(4)=AHC
      CB(5)=END
      CB(6)=SIDE
      CTX=CHX-CA(3)
      VHPST=(VEC*CA(1)+VFEST*CA(2)+VA*CA(4))/CTX
      HHPST=VHPST/(PQ*D2P)
      FL1=HEC+HA+HFEST+HHPST
      V1=PQ*D2P*FL1
      P=CA(2)/CTX
      FP=P/(P+1.0)
      FI=1.0-FP
      FPE=CA(5)/CTX
      FPS=CA(6)/CTX
      DEL=FL3-FL1
      TIMEX=1.0
      L=2
```

```
C     Statements removed here to prevent optimization.

      CALL CHEK(QI,FL2SV,FL3,T,L)
      FL3SV=FL3
      WRITE(6,675)
  675 FORMAT(15H STOP 1000      )
      CALL VERIFY(T)
  999 STOP
      END

      SUBROUTINE VERIFY(TIME)

C     This subroutine does not calculate cooling times, but arranges
C     results in order for rapid verification of the calculations.

      COMMON /SUBSTN/ FEHC,HPHC,AHC,ECHC
      COMMON /CALC/   PI,PQ,D2P,VEC,VA,VFEST,CHX,CA(6),CB(6),CC(6),
     1                CD(6),CE(6),CF(6),VHPST,HHPST,FL1,V1,P,FP,FI,
     2                FPE,FPS,VPIE,VPIS,CTX
      COMMON /DAT/    TMINOP,TMAXOP,TAL,TAH,D3,D2,GK4,GB4,END,SIDE,
     1                GK5,GB5,XPAN,DH,TIMEX,HGF,HGB
      COMMON /DNCITY/ DENFE,DENHP,DENA,DENEC
      COMMON /VERFY/ VFERS,VHPRS,FL2SV,FL3SV,VENDI,VSIDEI,CD1,CD2,CD3,
     1               CR1,CR2,CR3,TI1,TI2,TI3,TH1,TH2,TQM,RWX,RWY,R1,
     2               R2,R3,DT1,DT2,DT3,W1,W2,W3,T1,T2,T3

      DIMENSION HC(24)
      VIRON=VFEST+VFERS
      VHPLT=1.76548
      VH=    PI/4 *DH*DH*FL2SV
      VSUM= VEC+VA+VIRON+VHPLT+VH+VENDI+VSIDEI
      VTOTAL= PI/4 *D3*D3*FL3SV
      WRITE(6,1001) VEC, VA, VIRON, VHPLT, VH, VENDI, VSIDEI, VSUM,
     1              VTOTAL
 1001 FORMAT(
     1'                COOLING  TIME  VERIFICATION                 '/
     2' The results  for the  maximum  calculated  cooling time  are'/
     3' arranged below for  rapid verification  of the heat transfer'/
     4' calculations.                                              '/
     5                                                              /
     6' 1. Volume Check                                 '          /
     7'     a. Electrolyte-cathode              VEC    =',F12.7    /
     8'     b. Anode                            VA     =',F12.7    /
     9'     c. Iron                    VFEST + VFERS  =',F12.7    /
     1'     d. Heat pellet     VHPST + VHPRS +VPIE +VPIS =',F12.7    /
```

```
   2'    e. Center hole           (PI/4*DH*DH*FL2SV) =',F12.7    /
   3'    f. Insulation                            '          /
   4'             Volume end insulation =    VENDI   =',F12.7    /
   5'             Volume side insulation=    VSIDEI  =',F12.7    /
   6                                               /
   7'    g. Total Volume  (Sum of a to g, above)      =',F12.7    /
   8'    i. Total Volume (from case dimensions)       '          /
   9'                (PI/4 *D3*D3*FL3SV) =   VTOTAL =',F12.7   //)

    HC(1)=  VEC   *  CA(1)
    HC(2)=  VA    *  CA(4)
    HC(3)=  VIRON *  CA(2)
    HC(4)=  VHPLT *  CA(3)
    HC(5)=  VENDI *  CA(5)
    HC(6)=  VSIDEI*  CA(6)
    SUM2 =  HC(1)+HC(2)+HC(3)+HC(4)+HC(5)+HC(6)
    CALC =  CHX   *  VHPLT
    WRITE(6,1002) VEC, CA(1),HC(1),VA,CA(4),HC(2),VIRON,CA(2),HC(3),
   1             VHPLT, CA(3), HC(4),VENDI,CA(5),HC(5),VSIDEI,
   2             CA(6),HC(6),SUM2, CALC
1002 FORMAT(
   1' 2. Heat Balance (TAH to TMAXOP)                          '/
   2                                               /
   3'    Component',10X,'Volume',10X,'Ht. Cap.',9X,'Ht. Content  '/
   4'                    (cm3)',11X,'(cal/cm3)',10X,'(cal)    '/
   5                                               /
   6'   Elec-cathode    ',F12.7,   6X,  F10.6,   7X,    F12.6    /
   7'   Anode           ',F12.7,   6X,  F10.6,   7X,    F12.6    /
   8'   Iron            ',F12.7,   6X,  F10.6,   7X,    F12.6    /
   1'   Heat Pellet     ',F12.7,   6X,  F10.6,   7X,    F12.6    /
   2'   End Insulation  ',F12.7,   6X,  F10.6,   7X,    F12.6    /
   3'   Side Insulation ',F12.7,   6X,  F10.6,   7X,    F12.6    /
   4'                                ',17X, '---------   '/
   5'                             ',10X,'"SUM2"= ',F12.3   /
   6                                               /
   7'   Heat Supplied = CHX * VHP =',F12.3                    /
   8'(Heat Supplied may not equal "SUM2" for fixed length stack)'//)

    HC(1)=  VEC   *  CC(1)
    HC(2)=  VA    *  CC(4)
    HC(3)=  VIRON *  CC(2)
    HC(4)=  VHPLT *  CC(3)
    HC(5)=  VENDI *  CC(5)
    HC(6)=  VSIDEI*  CC(6)
    SUM3 =  HC(1)+HC(2)+HC(3)+HC(4)+HC(5)+HC(6)
    WRITE(6,1003) VEC, CC(1),HC(1),VA,CC(4),HC(2),VIRON,CC(2),HC(3),
```

```
   1          VHPLT, CC(3), HC(4), VENDI, CC(5), HC(5),
   2          VSIDEI, CC(6), HC(6), SUM3
1003 FORMAT(
   1' 3. Heat Balance (TAL to TQM)                    '/
   2                                        /
   3'   Component',10X,'Volume',10X,'Ht. Cap.',9X,'Ht. Content  '/
   4'               (cm3)',11X,'(cal/cm3)',10X,'(cal)    '/
   5                                        /
   6'   Elec-cathode    ',F12.7,   6X,  F10.6,   7X,    F12.6    /
   7'   Anode         ',F12.7,   6X,  F10.6,   7X,    F12.6    /
   8'   Iron         ',F12.7,   6X,  F10.6,   7X,    F12.6    /
   1'   Heat Pellet     ',F12.7,   6X,  F10.6,   7X,    F12.6    /
   2'   End Insulation  ',F12.7,   6X,  F10.6,   7X,    F12.6    /
   3'   Side Insulation ',F12.7,   6X,  F10.6,   7X,    F12.6    /
   2'                          ',17X, '---------   '/
   3'                          ',10X,'"SUM3"= ',F12.3  //
   4'   ("SUM3" should equal CHX * VHP)                 '//)

    HC(1)=  VEC   *  CB(1)
    HC(2)=  VA    *  CB(4)
    HC(3)=  VIRON *  CB(2)
    HC(4)=  VHPLT *  CB(3)
    HC(5)=  VENDI *  CB(5)
    HC(6)=  VSIDEI*  CB(6)
    SUM4 =  HC(1)+HC(2)+HC(3)+HC(4)+HC(5)+HC(6)
    WRITE(6,1004) VEC, CB(1),HC(1),VA,CB(4),HC(2),VIRON,CB(2),HC(3),
   1          VHPLT, CB(3), HC(4), VENDI, CB(5), HC(5),
   2          VSIDEI, CB(6), HC(6), SUM4
1004 FORMAT(
   1' 4. Heat Balance (TAL to TMINOP)                 '/
   2                                        /
   3'   Component',10X,'Volume',10X,'Ht. Cap.',9X,'Ht. Content  '/
   4'               (cm3)',11X,'(cal/cm3)',10X,'(cal)    '/
   5                                        /
   6'   Elec-cathode    ',F12.7,   6X,  F10.6,   7X,    F12.6    /
   7'   Anode         ',F12.7,   6X,  F10.6,   7X,    F12.6    /
   8'   Iron         ',F12.7,   6X,  F10.6,   7X,    F12.6    /
   1'   Heat Pellet     ',F12.7,   6X,  F10.6,   7X,    F12.6    /
   2'   End Insulation  ',F12.7,   6X,  F10.6,   7X,    F12.6    /
   3'   Side Insulation ',F12.7,   6X,  F10.6,   7X,    F12.6    /
   2'                          ',17X, '---------   '/
   3'                          ',10X,'"SUM4"= ',F12.3  //)

    CD3E =  CD(5) / 2.
    CD3S=   CD(6) / 2.
    HC(1)=  VEC   *  CD(1)
```

```
      HC(2)=  VA    *  CD(4)
      HC(3)=  VIRON *  CD(2)
      HC(4)=  VHPLT *  CD(3)
      HC(5)=  VENDI *  CD3E
      HC(6)=  VSIDEI*  CD3S
      SUM5 =  HC(1)+HC(2)+HC(3)+HC(4)+HC(5)+HC(6)
      WRITE(6,1005) VEC, CD(1),HC(1),VA,CD(4),HC(2),VIRON,CD(2),HC(3),
     1             VHPLT, CD(3), HC(4), VENDI, CD3E, HC(5),
     2             VSIDEI, CD3S, HC(6), SUM5
 1005 FORMAT(
     1' 5. Heat Available (TH1 to TQM)                        '/
     2                                         /
     3'    Component',10X,'Volume',10X,'Ht. Cap.',9X,'Ht. Content  '/
     4'                    (cm3)',11X,'(cal/cm3)',10X,'(cal)    '/
     5                                         /
     6'   Elec-cathode    ',F12.7,   6X,  F10.6,   7X,    F12.6    /
     7'   Anode           ',F12.7,   6X,  F10.6,   7X,    F12.6    /
     8'   Iron            ',F12.7,   6X,  F10.6,   7X,    F12.6    /
     1'   Heat Pellet     ',F12.7,   6X,  F10.6,   7X,    F12.6    /
     2'   End Insulation  ',F12.7,   6X,  F10.6,   7X,    F12.6    /
     3'   Side Insulation ',F12.7,   6X,  F10.6,   7X,    F12.6    /
     2'                                ',17X, '---------   '/
     3'                              ',10X,'"SUM5"= ',F12.6  //)

      CD3E =  CE(5) / 2.
      CD3S =  CE(6) / 2.
      HC(1)=  VEC   *  CE(1)
      HC(2)=  VA    *  CE(4)
      HC(3)=  VIRON *  CE(2)
      HC(4)=  VHPLT *  CE(3)
      HC(5)=  VENDI *  CD3E
      HC(6)=  VSIDEI*  CD3S
      SUM6 =  HC(1)+HC(2)+HC(3)+HC(4)+HC(5)+HC(6)
      WRITE(6,1006) VEC, CE(1),HC(1),VA,CE(4),HC(2),VIRON,CE(2),HC(3),
     1             VHPLT, CE(3), HC(4), VENDI, CD3E, HC(5),
     2             VSIDEI, CD3S, HC(6), SUM6
 1006 FORMAT(
     1' 6. Heat Available (TH2 to TH1)                        '/
     2                                         /
     3'    Component',10X,'Volume',10X,'Ht. Cap.',9X,'Ht. Content  '/
     4'                    (cm3)',11X,'(cal/cm3)',10X,'(cal)    '/
     5                                         /
     6'   Elec-cathode    ',F12.7,   6X,  F10.6,   7X,    F12.6    /
     7'   Anode           ',F12.7,   6X,  F10.6,   7X,    F12.6    /
     8'   Iron            ',F12.7,   6X,  F10.6,   7X,    F12.6    /
     1'   Heat Pellet     ',F12.7,   6X,  F10.6,   7X,    F12.6    /
```

```
   2'   End Insulation  ',F12.7,   6X,  F10.6,   7X,    F12.6    /
   3'   Side Insulation ',F12.7,   6X,  F10.6,   7X,    F12.6    /
   2'                                 ',17X, '---------   '/
   3'                              ',10X,'"SUM6"= ',F12.6  //)

    CD3E =  CF(5) / 2.
    CD3S =  CF(6) / 2.
    HC(1)=  VEC   *  CF(1)
    HC(2)=  VA    *  CF(4)
    HC(3)=  VIRON *  CF(2)
    HC(4)=  VHPLT *  CF(3)
    HC(5)=  VENDI *  CD3E
    HC(6)=  VSIDEI*  CD3S
    SUM7 =  HC(1)+HC(2)+HC(3)+HC(4)+HC(5)+HC(6)
    WRITE(6,1007) VEC, CF(1),HC(1),VA,CF(4),HC(2),VIRON,CF(2),HC(3),
   1            VHPLT, CF(3), HC(4), VENDI, CD3E, HC(5),
   2            VSIDEI, CD3S, HC(6), SUM7
1007 FORMAT(
   1' 7. Heat Available (TMINOP  to TH2)                         '/
   2                                            /
   3'    Component',10X,'Volume',10X,'Ht. Cap.',9X,'Ht. Content  '/
   4'                    (cm3)',11X,'(cal/cm3)',10X,'(cal)    '/
   5                                            /
   6'   Elec-cathode    ',F12.7,   6X,  F10.6,   7X,    F12.6    /
   7'   Anode          ',F12.7,   6X,  F10.6,   7X,    F12.6    /
   8'   Iron           ',F12.7,   6X,  F10.6,   7X,    F12.6    /
   1'   Heat Pellet     ',F12.7,   6X,  F10.6,   7X,    F12.6    /
   2'   End Insulation  ',F12.7,   6X,  F10.6,   7X,    F12.6    /
   3'   Side Insulation ',F12.7,   6X,  F10.6,   7X,    F12.6    /
   2'                                 ',17X, '---------   '/
   3'                              ',10X,'"SUM7"= ',F12.6  //)


    WRITE(6,1008) GK4,GB4,GK5,GB5,TQM,TH1,TH2,TMINOP,TAH,TAL,
   1            TI3,CD3,CR3,TI2,CD2,CR2,TI1,CD1,CR1

1008 FORMAT(
   1' 8.  Thermal conductivities (cal/sec-cm-C)                '/
   2                                            /
   3'    GK4 = ',E12.7,'   GB4 = ',E12.7,                        /
   4'    GK5 = ',E12.7,'   GB5 = ',E12.7,                        /
   5'    TQM = ',F7.3,' TH1 = ',F7.3,' TH2 = ',F7.3,' TMINOP = ',
   5          F7.3,/,'     TAH = ',F7.3,' TAL = ',F7.3          /
   6                                            /
   7'   a. Curve top                               '/
   8'      T3     = TQM - 0.5 * DTQ                          '/
```

```
   8'      TI3    = (T3 + TAL) * 0.5                          '/
   9'            = mean insulation temperature        = ',E12.7  /
   1'      KEND   = GK4 + GB4 * TI3 = CD3             = ',E12.7  /
   2'      KSIDE  = GK5 + GB5 * TI3 = CR3             = ',E12.7  /
   3                                          /
   4'    b. Curve center                              '/
   5'      T2     = T3- 1.0 * DTQ                       '/
   5'      TI2    = (T2 + TAL) * 0.5                    '/
   6'            = mean insulation temperature        = ',E12.7  /
   7'      KEND   = GK4 + GB4 * TI2 = CD2             = ',E12.7  /
   8'      KSIDE  = GK5 + GB5 * TI2 = CR2             = ',E12.7  /
   9                                          /
   1'    c. Curve bottom                               '/
   5'      T1     = T2- 1.0 * DTQ                       '/
   5'      TI1    = (T1 + TAL) * 0.5                    '/
   6'            = mean insulation temperature        = ',E12.7  /
   7'      KEND   = GK4 + GB4 * TI1 = CD1             = ',E12.7  /
   8'      KSIDE  = GK5 + GB5 * TI1 = CR1             = ',E12.7  /)

    WRITE(6,1009) RWX,RWY
1009 FORMAT(
   1'  9.  Geometric shape factors                    '/
   2                                          /
   3'    END plus EDGES    RWX  = '                     /
   4'    PI*((D2*D2*XPAN**2/(FL3SV-XPAN*FL2SV)+1.08*D2 *XPAN)= ',
   5     F10.3,' (cm)'                            //
   6'    SIDE     RWY = '                             /
   7'    PI* 2.0 *FL2SV*XPAN/ALOG(D3/D2/XPAN)             = ',F10.6,
   8     ' (cm)'                                 //)

    DT3 = T3 - TAL
    DT2 = T2 - TAL
    DT1 = T1 - TAL
    WRITE(6,1010) DT3,DT2,DT1
1010 FORMAT(
   1' 10.  Temperature differences:                   '/
   2                                          /
   3'    a. Curve top                                '/
   4'      DT3 = T3 - TAL           = ',F7.3,
   5      ' C'                                //
   6'    b. Curve center                              '/
   7'      DT2 = T2 - TAL           = ',F7.3,
   8      ' C'                                //
   9'    c. Curve bottom                               '/
   1'      DT1 = T1 - TAL           = ',F7.3,
   2      ' C'                                //)
```

```
      WRITE(6,1011) R3, R2, R1
1011 FORMAT(
     1' 11.  Heat loss rates:                              '/
     2                                               /
     3'    a. Curve top                                '/
     4'       R3  = RWX*DT3*CD3 + RWY*DT3*CR3              = ',F10.6,
     5       ' cal/sec'                                //
     6'    b. Curve center                             '/
     4'       R2  = RWX*DT2*CD2 + RWY*DT2*CR2              = ',F10.6,
     8       ' cal/sec'                                //
     9'    c. Curve bottom                             '/
     4'       R1  = RWX*DT1*CD1 + RWY*DT1*CR1              = ',F10.6,
     2       ' cal/sec'                                //)

      SUMW = W1 + W2 + W3
      WRITE(6,1012) W3, W2, W1, SUMW, TIME
1012 FORMAT(
     1' 12.  Cooling Times                                 '/
     2                                               /
     3'     The amount  of  heat  generated is  measured from  the '/
     4'     cooling  curves  and  inserted into  the cooling  time '/
     5'     equation  in  the  subroutine  CHEK.  Heat  generation '/
     6'     rates  increase  with  temperature and  decrease  with '/
     7'     time.                                      '/
     1                                               /
     2'    a. Curve top              W3 = (Q3 +HGF )/R3 = ',F10.6,
     3       ' sec'                                    //
     4'    b. Curve center           W2 = (Q2 + HGB)/R2 = ',F10.6,
     6       ' sec'                                    //
     7'    c. Curve bottom           W1 = Q1/R1         = ',F10.6,
     6       ' sec'                                    //
     7'    d. Total                  W1 + W2 + W3       = ',F10.6,
     8       ' sec'                                    /
     9'                                    TIME = ',F10.6,
     1       ' sec'                                    //
     2'    (Sum of W1 + W2 + W3 should equal "TIME")                '//)


      HC(1)= (CA(1)-17.5326 * DENEC)/((TMAXOP-TAH)*DENEC)
      HC(2)= (CA(4)-7.02 * DENA)/((TMAXOP-TAH)*DENA)
      HC(3)= CA(2)/((TMAXOP-TAH)*DENFE)
      HC(4)= CA(3)/((TMAXOP-TAH)*DENHP)

      HC(5)= (CC(1)-17.5326 * DENEC)/((TQM-TAL)*DENEC)
      HC(6)= (CC(4)-7.02 * DENA)/((TQM-TAL)*DENA)
```

```
      HC(7)= CC(2)/((TQM-TAL)*DENFE)
      HC(8)= CC(3)/((TQM-TAL)*DENHP)

      HC(9)= (CB(1)-17.5326 * DENEC)/((TMINOP-TAL)*DENEC)
      HC(10)= (CB(4)-7.02 * DENA)/((TMINOP-TAL)*DENA)
      HC(11)= CB(2)/((TMINOP-TAL)*DENFE)
      HC(12)= CB(3)/((TMINOP-TAL)*DENHP)

      HC(13)= CD(1)/((TQM-TH1)*DENEC)
      HC(14)= CD(4)/((TQM-TH1)*DENA)
      HC(15)= CD(2)/((TQM-TH1)*DENFE)
      HC(16)= CD(3)/((TQM-TH1)*DENHP)

      HC(17)= CE(1)/((TH1-TH2)*DENEC)
      HC(18)= CE(4)/((TH1-TH2)*DENA)
      HC(19)= CE(2)/((TH1-TH2)*DENFE)
      HC(20)= CE(3)/((TH1-TH2)*DENHP)

      HC(21)= CF(1)/((TH2-TMINOP)*DENEC)
      HC(22)= CF(4)/((TH2-TMINOP)*DENA)
      HC(23)= CF(2)/((TH2-TMINOP)*DENFE)
      HC(24)= CF(3)/((TH2-TMINOP)*DENHP)

      WRITE(6,1013) HC(1), HC(2), HC(3), HC(4), HC(5),
     1          HC(6), HC(7), HC(8), HC(9), HC(10),
     2          HC(11),HC(12),HC(13),HC(14),HC(15),
     3          HC(16),HC(17),HC(18),HC(19),HC(20),
     4          HC(21),HC(22),HC(23),HC(24)
 1013 FORMAT(
     1' 13.  Calculated specific heats  (cal/g-C)                    '/
     2                                                               /
     3'     The   calculated   specific   heats  of   the  battery '/
     4'     components  (cal/g-C)   are  easily  recognizable  and '/
     5'     generally increase slightly with  temperature.   These '/
     6'     values  are  printed out  below  as  an aid to program '/
     7'     debugging.                                               '/
     7                                                               /
     8'     a.  Specific heats (TAH to TMAXOP)                     '/
     9'        1. Electrolyte-cathode                            '/
     1'          (CA(1)-17.5326 * DENEC)/((TMAXOP-TAH)*DENEC) = ',
     2           F12.7                                         //
     3'        2. Anode                                        '/
     4'          (CA(4)-7.02 * DENA)/((TMAXOP-TAH)*DENA)   = ',
     5           F12.7                                         //
     6'        3. Iron                                        '/
     7'          CA(2)/((TMAXOP-TAH)*DENFE)                 = ',
```

```
8          F12.7                              //
3'      4. Heat Pellet                         '/
4'         CA(3)/((TMAXOP-TAH)*DENHP)               = ',
5          F12.7                              //
6'    b.  Specific heats (TAL to TQM)                 '/
8                                            /
9'      1. Electrolyte-cathode                    '/
1'         (CC(1)-17.5326 * DENEC)/((TQM-TAL)*DENEC)    = ',
2          F12.7                              //
3'      2. Anode                                '/
4'         (CC(4)-7.02 * DENA)/((TQM-TAL)*DENA)      = ',
5          F12.7                              //
6'      3. Iron                               '/
7'         CC(2)/((TQM-TAL)*DENFE)                  = ',
8          F12.7                              //
3'      4. Heat Pellet                         '/
4'         CC(3)/((TQM-TAL)*DENHP)                  = ',
5          F12.7                              //
6'    c.  Specific heats (TAL to TMINOP)               '/
8                                            /
9'      1. Electrolyte-cathode                    '/
1'         (CB(1)-17.5326 * DENEC)/((TMINOP-TAL)*DENEC) = ',
2          F12.7                              //
3'      2. Anode                                '/
4'         (CB(4)-7.02 * DENA)/((TMINOP-TAL)*DENA)   = ',
5          F12.7                              //
6'      3. Iron                               '/
7'         CB(2)/((TMINOP-TAL)*DENFE)               = ',
8          F12.7                              //
3'      4. Heat Pellet                         '/
4'         CB(3)/((TMINOP-TAL)*DENHP)               = ',
5          F12.7                              //
6'    d.  Specific heats (TQM to TH1)                 '/
7                                            /
8'      1. Electrolyte-cathode                    '/
9'         CD(1)/((TQM-TH1)*DENEC)                  = ',
1          F12.7                              //
2'      2. Anode                                '/
3'         CD(4)/((TQM-TH1)*DENA)                  = ',
4          F12.7                              //
5'      3. Iron                               '/
6'         CD(2)/((TQM-TH1)*DENFE)                  = ',
7          F12.7                              //
2'      4. Heat Pellet                         '/
3'         CD(3)/((TQM-TH1)*DENHP)                  = ',
4          F12.7                              //
```

```
     5'     e.  Specific heats (TH1 to TH2)                   '/
     6                                             /
     7'        1. Electrolyte-cathode                    '/
     8'           CE(1)/((TH1-TH2)*DENEC)                 = ',
     9            F12.7                              //
     1'        2. Anode                              '/
     2'           CE(4)/((TH1-TH2)*DENA)                 = ',
     3            F12.7                              //
     4'        3. Iron                             '/
     5'           CE(2)/((TH1-TH2)*DENFE)                = ',
     6            F12.7                              //
     1'        4. Heat Pellet                         '/
     2'           CE(3)/((TQ1-TH2)*DENHP)                 = ',
     3            F12.7                              //
     5'     f.  Specific heats (TH1 to TMINOP)                 '/
     6                                             /
     7'        1. Electrolyte-cathode                    '/
     8'           CF(1)/((TH2-TMINOP)*DENEC)              = ',
     9            F12.7                              //
     1'        2. Anode                              '/
     2'           CF(4)/((TH2-TMINOP)*DENA)              = ',
     3            F12.7                              //
     4'        3. Iron                             '/
     5'           CF(2)/((TH2-TMINOP)*DENFE)             = ',
     6            F12.7                              //
     1'        4. Heat Pellet                         '/
     2'           CF(3)/((TH2-TMINOP)*DENHP)              = ',
     3            F12.7                               )

      RETURN
      END
      SUBROUTINE MATERL(TLOW,THIGH)

C     This subroutine calculates the cal/cm3 values between TLOW and
C     THIGH for  iron, heat pellet, anode, electrolyte-cathode,  and
C     thermal insulation.

C  1= Fe      6= LiF(s)      11= LiCl(l)      16= Al(l)
C  2= FeO     7= LiF(l)      12= Li2O         17= Heat Pellet
C  3= KCl(s)  8= LiBr(s)     13= Li(s)        18= Anode
C  4= FeS2    9= LiBr(l)     14= Li(l)        19= Elec-Cathode
C  5= MgO    10= LiCl(s)     15= Al(s)        20=

C     PR1= Weight fraction Fe, FeO, KCl in burned heat pellet.
C     PR2= Weight fraction  LiF, LiBr, LiCl, Li, Al, in anode.
C     PR3= Weight fraction Fe, FeS2, MgO, LiF, LiBr, LiCl, in
```

```
C     electrolyte/cathode.
C     GMW= Gram molecular weights of first 16 substances.
C
C     703.15 K = 430 C = Melting point of LiF-LiBr-LiCl eutectic.
C     453.7  K = 180.55 C = Melting point of Lithium.
C     70.20 cal/g  = Heat of fusion of LiF-LiBr-LiCl eutectic.
C     17.5326 cal/g  = Heat of fusion of LiF-LiBr-LiCl eutectic in
C          electrolyte-cathode (70.2*(.O238872+.170860+.0550045
C          = 17.5326).
C     7.02 cal/g  = Heat of fusion of LiF-LiBr-LiCl eutectic in
C          anode (70.2*(.00956438+.0684120+.0220237)= 7.02).
C     70.2 x .1 = 7.02
C     All heat capacities calculated as sum of component
C     heat capacities.
C     Liquid lithium heat capacity used above 453.7 K.
C     T (K) = T (C) + 273.15


      COMMON /DAT/    TMINOP,TMAXOP,TAL,TAH,D3,D2,GK4,GB4,END,SIDE,
     1                GK5,GB5,XPAN,DH,TIMEX,HGF,HGB
      COMMON /SUBSTN/ FEHC,HPHC,AHC,ECHC
      COMMON /DNCITY/ DENFE,DENHP,DENA,DENEC
      DIMENSION PR1(16),PR2(16),PR3(16),GMW(16),DELH(20)

      DATA
     1 PR1/0.595687,0.318222,0.0861032,0.,0.,0.,0.,0.,0.,0.,0.,0.,0.,
     1 0.,0.,0./,
     2 PR2/0.,0.,0.,0.,0.,.00956438,0.,.0684120,0.,.0220237,0.,
     3    0.,0.18,0.,0.72,0./,
     4 PR3/0.0132193,0.,0.,0.515552,0.221478,.0238872,0.,.170860,0.,
     5    .0550045,0.,0.,0.,0.,0.,0./,
     6 GMW/55.85,68.89,74.56,119.98,40.32,25.94,25.94,86.86,86.86,
     7 42.40,42.40,29.88,6.940,6.940,26.98,26.98/

      T1=TLOW+273.15
      T2=THIGH+273.15
      DO  I=1,5
        DELH(I)=ENTG(T1,T2,I)/GMW(I)
      END DO
C     DELH(12) = ENTG(T1,T2,12)/GMW(12)

          IF(T2.LT.703.15) THEN
            DELH(6) = ENTG(T1,T2,6)/GMW(6)
            DELH(8) = ENTG(T1,T2,8)/GMW(8)
            DELH(10)= ENTG(T1,T2,10)/GMW(10)
          ELSE IF(T1.GT.703.15) THEN
```

```
          DELH(6) = ENTG(T1,T2,7)/GMW(7)
          DELH(8) = ENTG(T1,T2,9)/GMW(9)
          DELH(10)= ENTG(T1,T2,11)/GMW(11)
        ELSE
          DELH(6) = ENTG(T1,703.15,6)/GMW(6)
1               + ENTG(703.15,T2,7)/GMW(7)
          DELH(8) = ENTG(T1,703.15,8)/GMW(8)
1               + ENTG(703.15,T2,9)/GMW(9)
          DELH(10)= ENTG(T1,703.15,10)/GMW(10)
1               + ENTG(703.15,T2,11)/GMW(11)
        END IF
        IF(T2.LT.453.7) THEN
          DELH(13)= ENTG(T1,453.7,13)/GMW(13)
        ELSE IF(T1.GT.453.7) THEN
          DELH(13)= ENTG(T1,T2,14)/GMW(14)
        ELSE
          DELH(13)= ENTG(T1,453.7,13)/GMW(13)
1               + ENTG(453.7,T2,14)/GMW(14)
        END IF
        IF(T2.LT.932.0) THEN
          DELH(15)= ENTG(T1,T2,15)/GMW(15)
        ELSE IF(T1.GT.932.0) THEN
          DELH(15)= ENTG(T1,T2,16)/GMW(16)
        ELSE
          DELH(15)= ENTG(T1,932.0,15)/GMW(15)
1               + ENTG(932.0,T2,16)/GMW(16)
        END IF

      DELH(17)=0.0
      DELH(18)=0.0
      DELH(19)=0.0

      DO J= 1,16
        DELH(17)=DELH(J)*PR1(J)+DELH(17)
        DELH(18)=DELH(J)*PR2(J)+DELH(18)
        DELH(19)=DELH(J)*PR3(J)+DELH(19)
      END DO

      FEHC=DELH(1)*DENFE
      HPHC=DELH(17)*DENHP
      AHC=DELH(18)*DENA
      ECHC=DELH(19)*DENEC
      IF((T1.LT.703.11) .AND. (T2.GT.703.19)) THEN
        ECHC=(DELH(19)+17.5326)*DENEC
        AHC=(DELH(18)+7.02)*DENA
      END IF
```

```
      END =(.1716+.00009867*((T2+T1)*.5))*.0*(T2-T1)*.5
      SIDE=(.1716+.00009867*((T2+T1)*.5))*.0*(T2-T1)*.5
      RETURN
      END
      FUNCTION ENTG(T1,T2,J)
C     This function calculates the molar heat content between T1 and T2.
C     TR1, TR2, TR3 are molar heat capacity coefficients of the first
C     16 substances.

      DIMENSION TR1(16),TR2(16),TR3(16)
      DATA
     2 TR1/ 3.04, 11.66, 9.89, 17.88, 10.18, 10.41, 15.50, 11.50,
     3      16.00, 11.00, 16.00, 14.94, 1.64, 6.78, 4.94, 7.00/,
     4 TR2/ 0.00758, 0.002, 0.0052, 0.00132, .00174, 0.00390, 0.,
     5      0.00302, 0.0, .0034, 0.0, .00608, .0111, 0.0, .00296, 0.0/,
     6 TR3/ 60000., -67000., 77000.,-305000., -148000.,-138000., 0.,
     7      0., 0., 0., 0.,-338000., 84000., 99000., 0., 0./
      ENTG=(T2-T1)*TR1(J)+.5*(T2*T2-T1*T1)*TR2(J)-(1./T2-1./T1)*TR3(J)
      RETURN
      END

      SUBROUTINE DRV(FL2,FL3,DFL2)
C     This subroutine calculates the rate of change of stack length
C     with time

      FP=FL2+.0001
      FM=FL2-.0001
      CALL CHEK(QI,FP,FL3,TP,0)
      CALL CHEK(QI,FM,FL3,TM,0)
      DFL2=(TP-TM)/.0002
      RETURN
      END

      SUBROUTINE CHEK(QI,FL2,FL3,TIME,L)

C     This subroutine calculates the cooling times for various FL2.

C     FL2 is the length of the cell  stack plus the thermal reservoir
C     and the heat pellet required to heat the thermal insulation  in
C     centimeters.

C     The case  temperature is assumed to  remain unchanged when  the
C     unit is  fired at  TAL.  The  calculations are  therefore valid
C     under worst case heat sink conditions.

      COMMON /VERFY/ VFERS,VHPRS,FL2SV,FL3SV,VENDI,VSIDEI,CD1,CD2,CD3,
```

```
     1          CR1,CR2,CR3,TI1,TI2,TI3,TH1,TH2,TQM,RWX,RWY,R1,
     2          R2,R3,DT1,DT2,DT3,W1,W2,W3,T1,T2,T3
      COMMON/SUBSTN/ FEHC,HPHC,AHC,ECHC
      COMMON /CALC/  PI,PQ,D2P,VEC,VA,VFEST,CHX,CA(6),CB(6),CC(6),
     1          CD(6),CE(6),CF(6),VHPST,HHPST,FL1,V1,P,FP,FI,
     2          FPE,FPS,VPIE,VPIS,CTX
      COMMON /DAT/    TMINOP,TMAXOP,TAL,TAH,D3,D2,GK4,GB4,END,SIDE,
     1           GK5,GB5,XPAN,DH,TIMEX,HGF,HGB
      NAMELIST /OUT/ TIMEX,W1,W2,W3,Q1,Q2,Q3,R1,R2,R3,RWX,RWY,TQM,DTQ,
     1          FL1,FL2SV,HHPST,TH1,TH2
      NAMELIST /RIP/ CA,CB,CC,CD,CE,CF,VOLINS,V2,VEC,VA,VFEST,VFERS,
     1          VHPST,VHPRS,FP,FI,CHX,CHXT,CD3,CR3,CD2,CR2,CD1,CR1,
     2          V3,VENDI,VSIDEI,PILE,PILS,VPIE,VPIS,V2P,THPV,TFEV,
     3          FPE,FPS

C     Added Constant Values Here.


  331 V3=D3*D3*PQ*FL3
      V2=D2P*PQ*(FL2-FL1)
      VHPRS=0.0
      VFERS=0.0
      THPV=1.76548
      VHPLT=1.76548
      TFEV=.347500
      VFEST=.347500
      CHXT=2209.670

C     End Added Constants Here.

      TQL=TMINOP
      TQH=TMAXOP
C     TQM=  Maximum cell temperature reached from TAL.  Estimated
C          from 30 successive approximations.
      DO I= 1,30
        TQM=0.5*(TQL+TQH)
        CALL MATERL(TAL,TQM)
        CC(1)=ECHC
        CC(2)=FEHC
        CC(3)=HPHC
        CC(4)=AHC
        CC(5)=END
        CC(6)=SIDE
        QM= VEC*CC(1)+TFEV*CC(2)+THPV*CC(3)+VA*CC(4)+CC(5)*VENDI+
     1      CC(6)*VSIDEI
        QI= CHXT-QM
```

```
      IF(QI.LE.0.0) THEN
        TQH=TQM
      ELSE
        TQL=TQM
      END IF
    END DO
    DTQ=(TQM-TMINOP)/3.0
    T3=TQM-0.5*DTQ
    T2=T3-1.0*DTQ
    T1=T2-1.0*DTQ
    TI3=(T3+TAL)*0.5
    TI2=(T2+TAL)*0.5
    TI1=(T1+TAL)*0.5
    CD3=GK4+GB4*TI3
    CR3=GK5+GB5*TI3
    CD2=GK4+GB4*TI2
    CR2=GK5+GB5*TI2
    CD1=GK4+GB4*TI1
    CR1=GK5+GB5*TI1
    DT3=T3-TAL
    DT2=T2-TAL
    DT1=T1-TAL
    RWX=PI*(D2*D2*XPAN**2/(FL3-XPAN*FL2)+1.08*D2*XPAN)
    RWY=PI*2.0*FL2*XPAN/ALOG(D3/D2/XPAN)
    R3=RWX*DT3*CD3+RWY*DT3*CR3
    R2=RWX*DT2*CD2+RWY*DT2*CR2
    R1=RWX*DT1*CD1+RWY*DT1*CR1
    TH1=TQM-DTQ
    TH2=TH1-DTQ
    CALL MATERL(TH1,TQM)
    CD(1)=ECHC
    CD(2)=FEHC
    CD(3)=HPHC
    CD(4)=AHC
    CD(5)=(.1716+.00009867*((((TH1+273.15+TQM+273.15)*.5)+TAL+273.15)
   1*.5))*.752414*(TQM-TH1)
    CD(6)=(.1716+.00009867*((((TH1+273.15+TQM+273.15)*.5)+TAL+273.15)
   1*.5))*.752414*(TQM-TH1)
    Q3=VEC*CD(1)+TFEV*CD(2)+THPV*CD(3)+VA*CD(4)+CD(5)*VENDI/2.
   1  +CD(6)*VSIDEI/2.
C    HGF Calories are generated by the cells during W3
    W3=(Q3+HGF)/R3
    CALL MATERL(TH2,TH1)
    CE(1)=ECHC
    CE(2)=FEHC
    CE(3)=HPHC
```

```
      CE(4)=AHC
      CE(5)=(.1716+.00009867*((((TH1+273.15+TH2+273.15)*.5)+TAL+273.15)
     1*.5))*.752414*(TH1-TH2)
      CE(6)=(.1716+.00009867*((((TH1+273.15+TH2+273.15)*.5)+TAL+273.15)
     1*.5))*.752414*(TH1-TH2)
      Q2=VEC*CE(1)+TFEV*CE(2)+THPV*CE(3)+VA*CE(4)+CE(5)*VENDI/2.
     1 +CE(6)*VSIDEI/2.
C     HGB Calories are generated by the cells during W2
      W2=(Q2+HGB)/R2
      CALL MATERL(TMINOP,TH2)
      CF(1)=ECHC
      CF(2)=FEHC
      CF(3)=HPHC
      CF(4)=AHC
      CF(5)=(.1716+.00009867*((((TH2+273.15+TMINOP+273.15)*.5)+TAL+
     1 273.15)*.5))*.752414*(TH2-TMINOP)
      CF(6)=(.1716+.00009867*((((TH2+273.15+TMINOP+273.15)*.5)+TAL+
     1 273.15)*.5))*.752414*(TH2-TMINOP)
      Q1=VEC*CF(1)+TFEV*CF(2)+THPV*CF(3)+VA*CF(4)+CF(5)*VENDI/2.
     1  +CF(6)*VSIDEI/2.
      W1=Q1/R1
      TIME=W1+W2+W3
      IF(L.EQ.2) THEN
        WRITE(6,RIP)
        WRITE(6,OUT)
      END IF
      RETURN
      END
```

J-3. Output File

This is 14616 19 September 2008 19:09 gnft2so.

```
&herin  tminop=    435.000, tmaxop=    600.000, tal=   -40.0000, tah=    60.0000
 , denfe=    7.86000, denhp=    4.20000, dena=    1.50900, denec=    3.17908
 , fl3=    2.91000, hgf=    224.000, hgb=    112.000, d2=    1.90500, d3=
    2.91000, hec=   0.662940, ha=   0.548640, hfest=   0.121920, gk4=    3.90000E-04
 , gb4=    6.00000E-08, gk5=    3.90000E-04, gb5=    6.00000E-08, xpan=    1.00900
 , dh=  0.
 &end
 &rip  ca=    388.512    594.151    356.314    321.926  0.  0., cb=    329.187
    465.998    290.215    271.272  0.  0., cc=    412.314    623.768    380.614
    346.515  0.  0., cd=    27.8523    54.3737    30.8185    25.2586    6.98554
    6.98554, ce=    27.7117    52.5866    30.1324    25.0794    6.92130    6.92130
 , cf=    27.5628    50.8099    29.4485    24.9050    6.85705    6.85705
 , volins=  0., v2=   0.152600, vec=    1.88953, va=    1.56375, vfest=   0.347500
 , vfers=  0., vhpst=    1.61288, vhprs=  0., fp=   0.398910, fi=   0.601090
```

```
, chx=    1251.60, chxt=    2209.67, cd3=    4.04970E-04, cr3=    4.04970E-04
, cd2=    4.03722E-04, cr2=    4.03722E-04, cd1=    4.02474E-04, cr1=    4.02474E-04
, v3=    19.3539, vendi=    6.36541, vsidei=    7.42225, pile=  0., pils=  0.
, vpie=  0., vpis=  0., v2p=  0., thpv=    1.76548, tfev=   0.347500, fpe=  0.
, fps=  0.
&end
&out  timex=    1.00000, w1=    21.3846, w2=    30.5285, w3=    38.2966, q1=
   207.944, q2=    210.766, q3=    213.587, r1=    9.72401, r2=   10.57261
, r3=    11.4263, rwx=    18.8761, rwy=    29.8544, tqm=    559.804, dtq=
   41.6013, fl1=    1.89938, fl2sv=    1.95291, hhpst=   0.565876, th1=
   518.203, th2=    476.601
&end
STOP 1000
```

COOLING TIME VERIFICATION

The results for the maximum calculated cooling time are arranged below for rapid verification of the heat transfer calculations.

1. Volume Check
   a. Electrolyte-cathode VEC = 1.8895314
   b. Anode VA = 1.5637500
   c. Iron VFEST + VFERS = 0.3475000
   d. Heat pellet VHPST + VHPRS +VPIE +VPIS = 1.7654800
   e. Center hole (PI/4*DH*DH*FL2SV) = 0.0000000
   f. Insulation
      Volume end insulation = VENDI = 6.3654113
      Volume side insulation= VSIDEI = 7.4222507

   g. Total Volume (Sum of a to g, above) = 19.3539238
   i. Total Volume (from case dimensions)
      (PI/4 *D3*D3*FL3SV) = VTOTAL = 19.3539200

2. Heat Balance (TAH to TMAXOP)

Component	Volume (cm3)	Ht. Cap. (cal/cm3)	Ht. Content (cal)
Elec-cathode	1.8895314	388.512360	734.106262
Anode	1.5637500	321.925842	503.411560
Iron	0.3475000	594.150696	206.467361
Heat Pellet	1.7654800	356.313751	629.064819
End Insulation	6.3654113	0.000000	0.000000
Side Insulation	7.4222507	0.000000	0.000000

		"SUM2"=	2073.050

Heat Supplied = CHX * VHP = 2209.675
(Heat Supplied may not equal "SUM2" for fixed length stack)

3. Heat Balance (TAL to TQM)

Component	Volume (cm3)	Ht. Cap. (cal/cm3)	Ht. Content (cal)
Elec-cathode	1.8895314	412.313995	779.080200
Anode	1.5637500	346.515228	541.863220
Iron	0.3475000	623.768127	216.759415
Heat Pellet	1.7654800	380.614471	671.967224
End Insulation	6.3654113	0.000000	0.000000
Side Insulation	7.4222507	0.000000	0.000000

		"SUM3"=	2209.670

("SUM3" should equal CHX * VHP)

4. Heat Balance (TAL to TMINOP)

Component	Volume (cm3)	Ht. Cap. (cal/cm3)	Ht. Content (cal)
Elec-cathode	1.8895314	329.187164	622.009460
Anode	1.5637500	271.272247	424.201996
Iron	0.3475000	465.997803	161.934235
Heat Pellet	1.7654800	290.215057	512.368896
End Insulation	6.3654113	0.000000	0.000000
Side Insulation	7.4222507	0.000000	0.000000

		"SUM4"=	1720.515

5. Heat Available (TH1 to TQM)

Component	Volume (cm3)	Ht. Cap. (cal/cm3)	Ht. Content (cal)
Elec-cathode	1.8895314	27.852331	52.627853
Anode	1.5637500	25.258560	39.498074
Iron	0.3475000	54.373665	18.894848
Heat Pellet	1.7654800	30.818541	54.409519

End Insulation	6.3654113	3.492769	22.232912
Side Insulation	7.4222507	3.492769	25.924208

		"SUM5"=	213.587418

6. Heat Available (TH2 to TH1)

Component	Volume (cm3)	Ht. Cap. (cal/cm3)	Ht. Content (cal)
Elec-cathode	1.8895314	27.711700	52.362129
Anode	1.5637500	25.079411	39.217930
Iron	0.3475000	52.586636	18.273855
Heat Pellet	1.7654800	30.132429	53.198204
End Insulation	6.3654113	3.460648	22.028444
Side Insulation	7.4222507	3.460648	25.685795

		"SUM6"=	210.766357

7. Heat Available (TMINOP to TH2)

Component	Volume (cm3)	Ht. Cap. (cal/cm3)	Ht. Content (cal)
Elec-cathode	1.8895314	27.562794	52.080765
Anode	1.5637500	24.905033	38.945248
Iron	0.3475000	50.809948	17.656456
Heat Pellet	1.7654800	29.448462	51.990669
End Insulation	6.3654113	3.428526	21.823978
Side Insulation	7.4222507	3.428526	25.447378

		"SUM7"=	207.944489

8. Thermal conductivities (cal/sec-cm-C)

GK4 = .3900000E-03 GB4 = .6000000E-07
GK5 = .3900000E-03 GB5 = .6000000E-07
TQM = 559.804 TH1 = 518.203 TH2 = 476.601 TMINOP = 435.000
TAH = 60.000 TAL = -40.000

a. Curve top
T3 = TQM - 0.5 * DTQ
TI3 = (T3 + TAL) * 0.5

= mean insulation temperature = .2495016E+03
KEND = GK4 + GB4 * TI3 = CD3 = .4049701E-03
KSIDE = GK5 + GB5 * TI3 = CR3 = .4049701E-03

b. Curve center
T2 = T3- 1.0 * DTQ
TI2 = (T2 + TAL) * 0.5
= mean insulation temperature = .2287010E+03
KEND = GK4 + GB4 * TI2 = CD2 = .4037220E-03
KSIDE = GK5 + GB5 * TI2 = CR2 = .4037220E-03

c. Curve bottom
T1 = T2- 1.0 * DTQ
TI1 = (T1 + TAL) * 0.5
= mean insulation temperature = .2079003E+03
KEND = GK4 + GB4 * TI1 = CD1 = .4024740E-03
KSIDE = GK5 + GB5 * TI1 = CR1 = .4024740E-03

9. Geometric shape factors

END plus EDGES RWX =
PI*((D2*D2*XPAN**2/(FL3SV-XPAN*FL2SV)+1.08*D2 *XPAN)= 18.876 (cm)

SIDE RWY =
PI* 2.0 *FL2SV*XPAN/ALOG(D3/D2/XPAN) = 29.854393 (cm)

10. Temperature differences:

a. Curve top
DT3 = T3 - TAL = 579.003 C

b. Curve center
DT2 = T2 - TAL = 537.402 C

c. Curve bottom
DT1 = T1 - TAL = 495.801 C

11. Heat loss rates:

a. Curve top
R3 = RWX*DT3*CD3 + RWY*DT3*CR3 = 11.426271 cal/sec

b. Curve center
R2 = RWX*DT2*CD2 + RWY*DT2*CR2 = 10.572611 cal/sec

c. Curve bottom
R1 = RWX*DT1*CD1 + RWY*DT1*CR1 = 9.724012 cal/sec

12. Cooling Times

The amount of heat generated is measured from the cooling curves and inserted into the cooling time equation in the subroutine CHEK. Heat generation rates increase with temperature and decrease with time.

a. Curve top W3 = (Q3 +HGF)/R3 = 38.296604 sec

b. Curve center W2 = (Q2 + HGB)/R2 = 30.528538 sec

c. Curve bottom W1 = Q1/R1 = 21.384638 sec

d. Total W1 + W2 + W3 = 90.209778 sec
TIME = 90.209778 sec

(Sum of W1 + W2 + W3 should equal "TIME")

13. Calculated specific heats (cal/g-C)

The calculated specific heats of the battery components (cal/g-C) are easily recognizable and generally increase slightly with temperature. These values are printed out below as an aid to program debugging.

a. Specific heats (TAH to TMAXOP)

1. Electrolyte-cathode
(CA(1)-17.5326 * DENEC)/((TMAXOP-TAH)*DENEC) = 0.1938453

2. Anode
(CA(4)-7.02 * DENA)/((TMAXOP-TAH)*DENA) = 0.3820689

3. Iron
CA(2)/((TMAXOP-TAH)*DENFE) = 0.1399846

4. Heat Pellet
CA(3)/((TMAXOP-TAH)*DENHP) = 0.1571048

b. Specific heats (TAL to TQM)

1. Electrolyte-cathode
(CC(1)-17.5326 * DENEC)/((TQM-TAL)*DENEC) = 0.1870001

2. Anode
(CC(4)-7.02 * DENA)/((TQM-TAL)*DENA) = 0.3711419

3. Iron
CC(2)/((TQM-TAL)*DENFE) = 0.1323096

4. Heat Pellet
CC(3)/((TQM-TAL)*DENHP) = 0.1510869

c. Specific heats (TAL to TMINOP)

1. Electrolyte-cathode
(CB(1)-17.5326 * DENEC)/((TMINOP-TAL)*DENEC) = 0.1810849

2. Anode
(CB(4)-7.02 * DENA)/((TMINOP-TAL)*DENA) = 0.3636833

3. Iron
CB(2)/((TMINOP-TAL)*DENFE) = 0.1248153

4. Heat Pellet
CB(3)/((TMINOP-TAL)*DENHP) = 0.1454712

d. Specific heats (TQM to TH1)

1. Electrolyte-cathode
CD(1)/((TQM-TH1)*DENEC) = 0.2105974

2. Anode
CD(4)/((TQM-TH1)*DENA) = 0.4023577

3. Iron
CD(2)/((TQM-TH1)*DENFE) = 0.1662873

4. Heat Pellet
CD(3)/((TQM-TH1)*DENHP) = 0.1763826

e. Specific heats (TH1 to TH2)

1. Electrolyte-cathode
CE(1)/((TH1-TH2)*DENEC) = 0.2095340

2. Anode
CE(4)/((TH1-TH2)*DENA) = 0.3995039

3. Iron
CE(2)/((TH1-TH2)*DENFE) = 0.1608221

4. Heat Pellet
CE(3)/((TQ1-TH2)*DENHP) = 0.1724558

f. Specific heats (TH1 to TMINOP)

1. Electrolyte-cathode
CF(1)/((TH2-TMINOP)*DENEC) = 0.2084081

2. Anode
CF(4)/((TH2-TMINOP)*DENA) = 0.3967261

3. Iron
CF(2)/((TH2-TMINOP)*DENFE) = 0.1553886

4. Heat Pellet
CF(3)/((TH2-TMINOP)*DENHP) = 0.1685413

List of Symbols, Acronyms, and Abbreviations

ARDEC	U.S. Army Research and Development Command
ARL	U.S. Army Research Laboratory
ATO	Army Technical Objective
GC	Gas Chromatograph
LCCM	Low Cost Competent Munition
RPS	revolutions per second
RTF	reusable test fixture
SS	stainless steel

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